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# Technologies and policy levers for more sustainable batteries

Alexander Tankou, Dale Hall

ZEV ALLIANCE

The International Zero-Emission Vehicle Alliance is a network of leading national and sub-national governments demonstrating their deep commitment to accelerating the transition to zero-emission vehicles within their markets and globally. Its members include Austria, Baden-Württemberg, British Columbia, California, Canada, Chile, Connecticut, Costa Rica, Germany, Maryland, Massachusetts, the Netherlands, New Jersey, New York, New Zealand, Norway, Oregon, Québec, Rhode Island, the United Kingdom, Vermont, and Washington. The members collaborate through discussion of challenges, lessons learned, and opportunities; hosting events with governments and the private sector; and by commissioning research on the most pressing issues in the ZEV transition.

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secretariat@zevalliance.org | www.zevalliance.org

# Executive summary

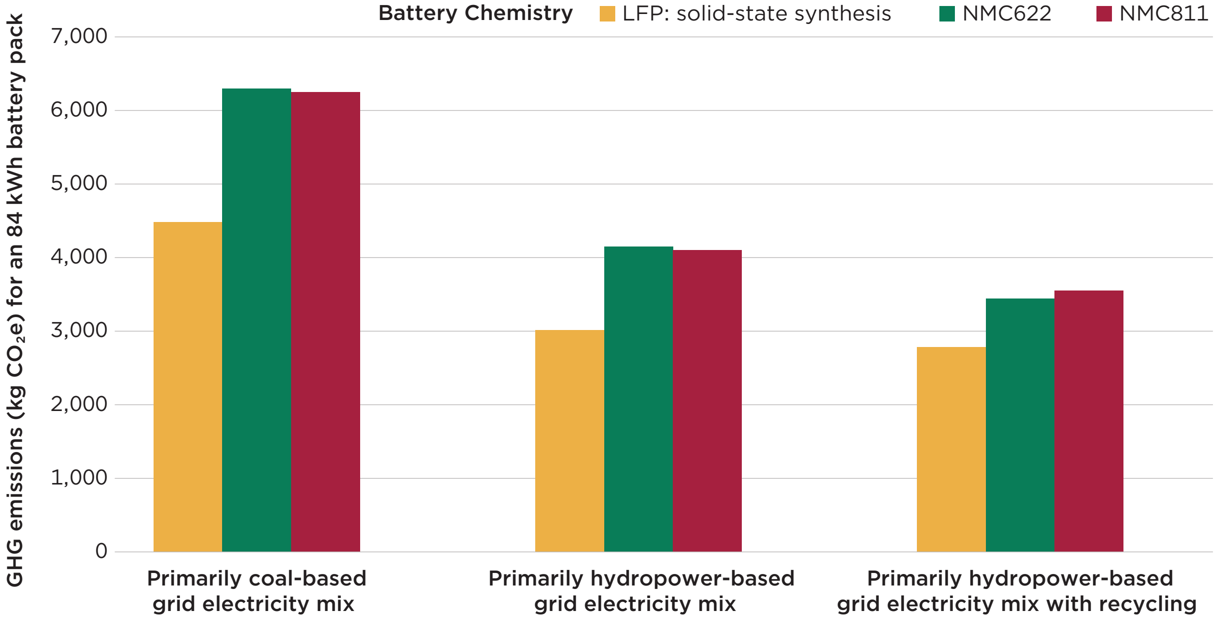
As global demand for electric vehicles (EVs) accelerates—driven by the imperative to transition to a low-carbon economy—the mining industry faces increasing pressure to adopt more sustainable and responsible practices as it scales up the production of minerals. The EV market is heavily reliant on key minerals such as lithium, cobalt, nickel, and graphite for lithium-ion batteries. The processing of these minerals and the manufacturing of EV batteries account for a significant part of EV production emissions, comprising at least one third of total embedded emissions (Linder et al., 2023; Negri & Bieker, 2025a). Besides these emissions, conventional mining practices can also result in environmental degradation, natural resource depletion, and human rights violations.

This report assesses technological and policy options for reducing the environmental and social impacts of battery material mining and battery production. It finds that although EVs already offer major climate benefits over combustion vehicles, there are many ways to further reduce the climate impacts of EV batteries and support more responsible supply chains.

The report begins by establishing the climate benefits of EVs and assessing whether mineral supplies can meet projected demand. It then examines current mineral extraction and processing practices and their environmental impacts, reviews the extent to which mining companies and automakers have integrated voluntary environmental, social, and governance principles, and explores technological pathways for reducing the carbon footprint of batteries. Finally, the report outlines key government policies to strengthen the alignment of battery supply chains with sustainability goals.

The report examines how multiple parameters—including electricity sources, battery chemistry, cathode production pathways, and recycling—influence the carbon footprint of EV batteries. Figure ES1 displays a subset of the results, showing the greenhouse gas (GHG) emissions for battery packs manufactured in three different electricity grid scenarios: one using a primarily coal-based electricity grid mix (similar to grids in China), one using a primarily hydropower-based electricity grid mix (similar to the grid in Norway), and a third using materials recycled via hydrometallurgy with 50% recycled lithium and 90% recycled cobalt and nickel in a hydropower-based grid.
All findings related to GHG emissions are based on the 2024 data inventory of the Research & Development Greenhouse gases, Regulated Emissions, and Energy use in Technologies (R&D GREET) model, which may differ from other inventories.

**Figure ES1.** Life-cycle analysis of battery chemistries produced in different electricity grid scenarios




*Note:* LFP = lithium iron phosphate; NMC622 = nickel manganese cobalt (6:2:2); NMC811 = nickel manganese cobalt (8:1:1).

The figure illustrates that batteries produced in regions where the grid is more carbon intensive have substantially higher GHG emissions than those produced in regions where the electricity mix relies on renewable energy. Furthermore, incorporating recycled material from end-of-life batteries into new batteries, particularly when using hydrometallurgical processes, generates lower emissions compared with using only virgin materials.

The report draws the following conclusions for mitigating GHG emissions and addressing other challenges relating to batteries and their production:

**Using renewable energy in battery manufacturing and adopting innovative battery technologies present the greatest opportunities to reduce batteries' embedded GHG emissions.** As indicated in Figure ES1, the carbon intensity of lithium-ion batteries is sensitive to the battery design and manufacturing energy source. While this analysis found that lithium iron phosphate (LFP) batteries may have lower embedded GHG emissions than nickel manganese cobalt (NMC) batteries on a per kWh basis, the emission intensities of these two dominant chemistries could be higher or lower depending on specific materials and processes. As of 2025, prospective battery chemistries—such as solid-state and sodium-ion—tend to exhibit higher life-cycle emissions compared with technologically mature chemistries like LFP and NMC. Ongoing technological progress and the realization of economies of scale could change these trends over time. Across all chemistries, switching from fossil fuels to electricity and increasing the share of renewable and low-carbon electricity result in meaningful reductions in a battery's carbon footprint. Our analysis found that producing batteries on a renewables-based electricity grid instead of a high-carbon electricity grid can lower a battery's carbon footprint by 30%–40%.

**Although mining of key battery materials can inflict environmental damage, it represents only a small share of batteries' GHG footprint.** Mining can cause significant air, water, and soil pollution and resource depletion, affecting local communities and ecosystems. However, environmentally responsible practices can be deployed to reduce this damage. In contrast to mining, refining and processing of battery minerals like lithium, nickel, and cobalt are typically very energy intensive and account for 5 to 50 times more emissions than the mining of those same minerals. Overall, the mining, processing, and refining of key battery materials (i.e., lithium hydroxide, nickel sulfate, cobalt sulfate, manganese sulfate, and graphite) together account for about half of a nickel-rich NMC battery's GHG footprint, depending on the source of the mineral.

**Reducing the need for mining and new batteries through improved battery durability and recycling are among the most effective ways to reduce emissions from the sector.** Governments can reduce the number of battery replacements needed by implementing durability requirements, such as regulations in California and the European Union that require a 70%–72% battery storage capacity or state-of-health after 5–8 years or 160,000 km. Ensuring that batteries are recycled can also reduce emissions. Using materials derived from hydrometallurgical recycling in the production of a new battery could reduce its carbon footprint by 13%–17% compared with producing the same battery with newly mined materials.

**Governments can align battery certification schemes, guidelines, and standards to promote responsible mining and sustainable battery manufacturing at scale.** Independent experts and international organizations like the Organisation for Economic Co-operation and Development, the Office of the United Nations High Commissioner for Human Rights, the Initiative for Responsible Mining Assurance, and the Responsible Minerals Initiative have created robust certification or assessment programs and due diligence guidelines, but these programs are rarely given the force of law. Alignment around these existing frameworks, achievable by integrating similar requirements into incentive schemes or vehicle regulations, would enable the industry to harmonize around a common set of standards, resulting in greater benefits while reducing the cost of compliance.

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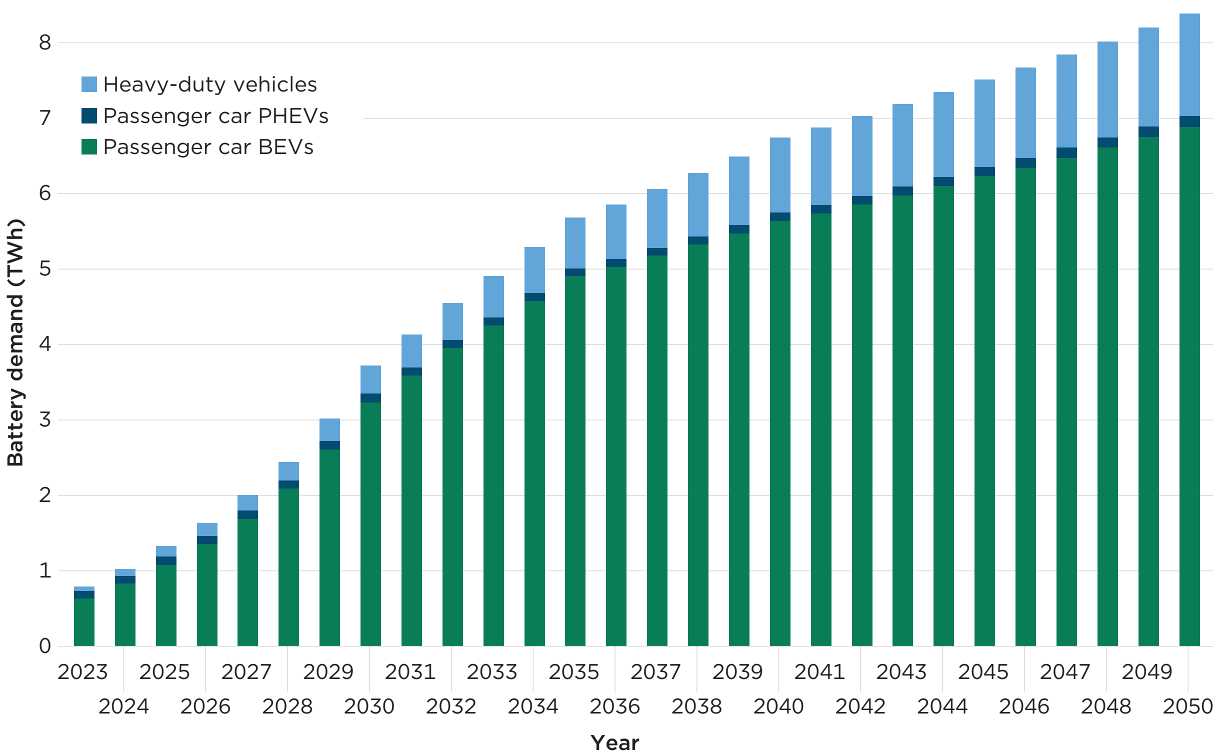
# Introduction

The transition toward electric vehicles (EVs)[1] is motivated by the potential to mitigate climate change and air pollution as well as to develop new industries and promote energy independence. An increasing number of governments are introducing regulations, EV sales targets, and fiscal policies, among other measures, to ensure that global emissions from the transportation sector align with the Paris Agreement goal of limiting global warming to well below 2 °C.

At the core of this transition is the lithium-ion battery, which has seen consistent cost reductions and performance improvements as a result of innovation and economies of scale (BloombergNEF, 2024; European Alternative Fuels Observatory, n.d.; Randall, 2024). Under a scenario consistent with adopted, announced, and proposed policies, demand for batteries to serve electric light-duty vehicles (cars and light commercial vehicles) and heavy-duty vehicles is expected to increase from about 1 TWh in 2024 to 3.8 TWh in 2030 and 8.7 TWh in 2050, an eightfold increase (Figure 1).

**Figure 1.** Historic and projected global battery demand




*Source:* Li et al. (2024)

Against this background, concerns persist among consumers, frontline communities, advocacy groups, and governments regarding the environmental and social impacts of EV supply chains. Research has found that the extraction and processing of minerals result in greenhouse gas (GHG) emissions and adverse environmental impacts, including deforestation, land degradation, and water contamination (Oxfam Australia, 2025; Shafique & Luo, 2022). In some instances, mineral extraction has also been linked to social abuses, including workers' exposure to toxic substances and the use

1 Unless otherwise specified, EVs refer to both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) in this report, because BEVs and PHEVs use similar battery technologies.

of child labor (Amnesty International, 2016). In certain contexts, mining has heightened existing social tensions and conflicts (International Institute for Sustainable Development, 2018). However, when well-managed, mining can also provide benefits to local communities in the form of job creation and investment (Oxfam Australia, 2025).

This report describes available technologies and policy approaches to support more environmentally and socially responsible EV battery supply chains. The first section summarizes research findings on the life-cycle environmental impact of EVs and compares the mineral demand from the EV transition with mineral supply. The second section describes common practices of conventional mining and processing. It details the carbon footprint of key intermediate materials used to produce EV batteries and discusses technological pathways to reduce their associated GHG emissions; it also provides an overview of the extent to which the mining sector and automakers integrate environmental, social, and governance (ESG) principles within their operations. The third section offers insights into the deployment of renewable energies in mineral extraction and processing, as well as manufacturing approaches for lower-carbon batteries. The fourth section provides an overview of the international frameworks that address environmental and social impacts of enterprises like the EV supply chain, highlighting their potential as well as their limitations. We conclude the report by identifying policies and regulations that promote more responsible and sustainable EV battery supply chains.

## Scope and limitations

This report focuses on the environmental and social impacts of lithium-ion battery supply chains, emphasizing the mining and processing of minerals that are especially critical to EV batteries—specifically, lithium, cobalt, nickel, graphite, and manganese. Other battery materials like aluminum, copper, and graphite are not discussed in detail. Our analysis relies primarily on the Research & Development Greenhouse gases, Regulated Emissions, and Energy use in Technologies (R&D GREET 2024) model (Wang et al., 2024) and reflects regional or national averages rather than site-specific conditions. The quantitative analysis focuses on GHG emissions and does not analyze other criteria such as toxicity, air pollution, water use, or water pollution.

Several aspects receive limited coverage, such as the embedded emissions of other vehicle components and end-of-life management beyond recycling technology. While emerging technologies like solid-state batteries are discussed, the primary focus remains on the commercialized lithium-ion chemistries dominating the 2025 market: lithium iron phosphate (LFP), nickel manganese cobalt (NMC), and nickel cobalt aluminum (NCA). Future technological developments may alter the considerations presented here.

# Background: EV climate benefits and mineral supply

To contextualize the environmental considerations of battery supply chains, it is useful to first establish the climate benefits that EVs provide relative to conventional vehicles and assess the availability of mineral supplies to support the projected growth in EV adoption. This section summarizes the consensus on these foundational concepts.

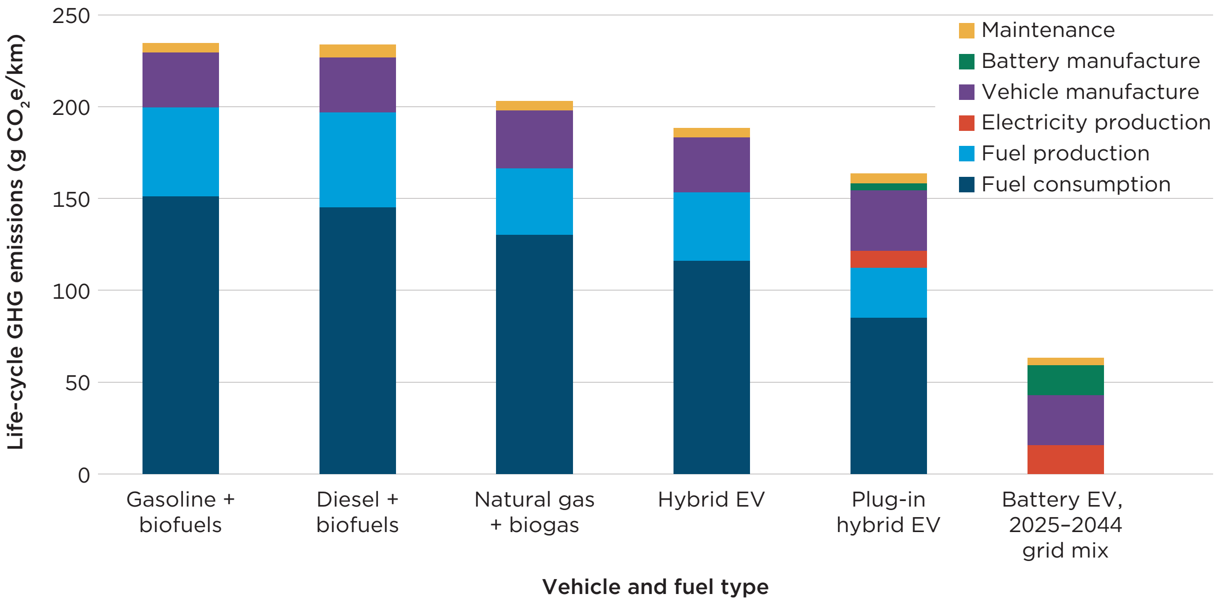
## Environmental footprint of EVs compared with conventional vehicles

When analyzing the climate and environmental impacts of EVs, it is important to weigh them in relation to the impacts of internal combustion engine vehicles (ICEVs), which EVs are supplanting. Life-cycle assessment (LCA) studies, which look at the emissions involved in the production, use, and end of life of a product, aim to provide a thorough inventory of these emissions. These studies generally include quantifying GHG emissions over a vehicle's lifetime, typically expressed in grams of carbon dioxide equivalent ($CO_2e$) per kilometer driven.

While methodologies and assumptions might differ, most research finds that throughout their life cycle, EVs emit less GHGs than their ICEV counterparts, even in regions with relatively carbon-intensive electricity. This is despite the fact that manufacturing EVs produces higher GHG emissions than manufacturing ICEVs, mostly due to emissions associated with the lithium-ion battery (Hill et al., 2023; Linder, 2023; Negri & Bieker, 2025a). A report commissioned by the European Commission found that, in the European Union (EU), a new BEV SUV sold in 2020 was expected to reduce GHG emissions by over 60% compared with a conventional gasoline vehicle over a period of 15 years (Hill et al., 2023).

These findings align with International Council on Clean Transportation (ICCT) LCA studies of passenger cars in China, Europe, India, and the United States (Bieker, 2021; Negri & Bieker, 2025a; O'Malley & Slowik, 2024). These studies found that throughout their lifetime, BEVs have GHG emissions that are 73%–78% lower than gasoline cars in Europe, 66%–70% in the United States, 37%–45% in China, and 19%–34% in India. As an example, Figure 2 illustrates the key results of Negri and Bieker's (2025a) EU-wide LCA study.

**Figure 2.** Life-cycle GHG emissions of medium segment passenger cars sold in the EU



Furthermore, an analysis by the International Energy Agency (IEA) assessed global average life-cycle GHG emissions (in metric tons of $CO_2e$ over a vehicle's lifetime) for medium-sized cars across different powertrains—including ICEVs, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs)—based on vehicles sold in 2023 and 2035 with an estimated lifetime of 15 years or approximately 200,000 km (IEA, 2024a). The analysis indicated that, under the Stated Policies Scenario, the life-cycle emissions of a medium-sized BEV sold in 2023 were about 50% lower than those of a comparable ICEV, more than 40% lower than an HEV, and around 30% lower than a PHEV.[2] Consistent with Bieker (2021), the IEA also found that electricity production is the largest contributor to a BEV's lifetime emissions (about 60% of the total), underscoring the importance of continued decarbonization of the power sector. Under the Announced Pledges Scenario, BEV emissions reductions improved by an additional 5% due to faster integration of clean energy into the grid over time.

Finally, an analysis representing 2025 conditions reiterated the environmental advantage of BEVs in relation to their ICEV counterparts. A study by the U.S. Department of Energy found that a light-duty sport utility BEV purchased in the United States in 2025 would produce 46% fewer GHG emissions per mile vis-à-vis a comparable gasoline vehicle, even when using the conservative assumption that the electricity mix would remain constant throughout the lifetime of the vehicle. In actuality, electricity will likely continue to shift toward lower-carbon sources; if charged using the projected 2035 grid mix, the emissions reductions of the 2025 BEV relative to a gasoline vehicle would widen to 76% (U.S. Department of Energy, 2025).

In sum, our survey of the scientific literature offers clear support for the conclusion that EVs produce fewer GHG emissions than comparable ICEVs across most major markets. A continued shift toward a low-carbon electricity mix will be important to maximize the environmental benefits of EVs. Furthermore, as we discuss later in this report, the life-cycle emissions of batteries are sensitive to mining and processing techniques and the battery's specific chemistry, as well as the pathways chosen once batteries reach end of life. Strategic selection of low-carbon production methods and recycling routes can mitigate these emissions.

## Comparing mineral demand and supply for the EV transition

An increasing number of governments are introducing policies to accelerate EV sales, with many committing to reach 100% light-duty zero-emission vehicle (ZEV) sales by 2035 (Hall, 2024; ICCT, 2025). The IEA found that the demand for lithium-ion batteries reached more than 750 GWh in 2023, equivalent to a 40% increase relative to 2022. EVs accounted for 95% of this increased demand due to growing sales as well as larger battery sizes (IEA, 2024a). This raises the question of whether there are enough minerals to enable a global EV transition. The IEA found that supply of key minerals has increased alongside the demand for batteries, exceeding this demand in 2023 by 10% for lithium, 6.5% for cobalt, and 8% for nickel (IEA, 2024a).

Several studies have also projected mineral demand for EV batteries and compared it with estimated supply. The ICCT's 2024 *Global and Regional Battery Material Outlook* estimated the battery demand based on current, announced, and proposed road transport electrification policies and targets globally, predicting that it would be 4 TWh in 2030, including the demand from

2 The Stated Policies Scenario models energy policies in place or under development as of September 2024. Meanwhile, the Announced Pledges Scenario reflects country and industry climate-related commitments as of September 2024, including nationally determined contributions and longer-term net-zero targets, among others, due to faster integration of clean energy into the grid over time.

stationary and other battery applications. This is compared with battery cell production capacities of 8 TWh in 2030 for all announced projects and 6 TWh when considering only those projects that are already operational or highly probable (Li et al., 2024). However, this scenario results in a global temperature increase above 2 °C, meaning that more ambitious policies—and, potentially, higher demand for minerals in the near and medium term—would be required to align with the Paris Agreement goals.

The report further found that the anticipated 2030 mining capacities for lithium, nickel, and cobalt are sufficient and may even exceed the demand from batteries and all other applications of these minerals. When comparing the accumulated mineral demand between 2023 and 2050 with global reserves identified as of 2024, the report found that the cumulative demand for lithium corresponded to 49% of these identified reserves, compared with 38% for cobalt, 2% for nickel, and 8% for natural graphite reserves.[3] These projections are likely overestimates, as new battery technologies expected to be commercialized in the future will reduce aggregate demand for these three minerals.

Additionally, a report by the International Renewable Energy Agency (IRENA) modeled the demand for an accelerated EV transition consistent with limiting global warming to 1.5 °C. In this scenario, battery demand from electric cars, SUVs, vans, trucks, motorcycles, and buses would surpass 4,300 GWh per year by 2030, equivalent to 5 times the demand in 2023. For comparison, current and planned battery production capacity is expected to reach 7,300 GWh per year in 2030. Although this exceeds expected demand, this production capacity is not exclusive to EVs and includes other applications such as stationary energy storage and electronics. The report highlighted that in an accelerated electrification scenario there are some uncertainties as to whether planned minerals and refining capacity will materialize due to factors such as mineral price fluctuations, disruption from natural disasters, and political tensions. To address these potential supply bottlenecks, the report highlighted the need for concerted efforts among stakeholders for faster deployment of mining and processing projects. Looking more long term, improvements in recycling recovery pathways or the deployment of sodium-ion batteries could ease pressure on lithium-ion battery supply chains and help manage these uncertainties (IRENA, 2024).

To conclude, multiple estimates as of 2024 suggest that existing mineral reserves are likely sufficient to support projected EV market growth through 2050 under current and announced policies, even when only assuming the use of commercially deployed battery technologies as of 2024. In addition, operating, announced, and highly probable battery cell production capacities are expected to exceed projected global battery demand—for both vehicular and non-vehicular applications—at least through 2030 (Li et al., 2024). Aside from highlighting the feasibility of currently discussed transport electrification policies and targets, Li et al. (2024) showed that the raw material mining demand for achieving these targets can be managed through a mix of battery technology innovation, recycling, reduction in EV battery size, and the promotion of transport avoid-and-shift measures. A global battery demand trajectory more closely aligned with a highly ambitious 1.5 °C climate target introduces greater supply uncertainties, emphasizing the need for effective collaborations among key stakeholders to accelerate deployment of mining and refining activities as well as technology innovations (IRENA, 2024).

3 Reserves only correspond to the proportion of total resources that are economically feasible to exploit today. Given advances in mineral exploration and mining technology, the number of deposits classified as reserves continues to increase, as exemplified by global lithium reserves that have increased by 83% from Q1 2018 to Q1 2023 (Silva, 2023).

# Current practices: Mining, processing, and their impacts

Having established that EVs offer substantial climate benefits and that mineral supplies appear adequate to meet projected demand, we now turn to examining how these minerals are typically extracted and processed in addition to the environmental and social impacts of these operations.

Understanding the approaches used to mine, process, and refine battery minerals provides context for their carbon footprint and illuminates opportunities to reduce their embedded emissions. Before a battery can be produced, the constituent minerals must be extracted, refined, and transported to other locations for further production. The processes for extraction and refining, and the associated emissions, vary significantly according to the mineral (e.g., lithium, nickel, copper), its source (e.g., brine vs. hard rock), and the intermediate product (e.g., lithium carbonate [$Li_2CO_3$] or lithium hydroxide [LiOH]).

This section first describes the techniques for mining and processing lithium and cobalt—two of the key minerals in lithium-ion batteries—to illustrate how production methods influence the carbon footprint of battery supply chains. It then describes the typical energy sources powering these operations as of 2025. These two factors—production methods and energy sources—are then integrated into a quantitative assessment of the GHG emissions associated with key intermediate battery materials; this assessment demonstrates which of these materials contribute the most GHG emissions in the production of NMC811 batteries and, by extension, where emission reduction efforts could be most effective. Finally, we address the broader environmental and social impacts of mineral extraction beyond climate considerations—including water use, biodiversity loss, and labor conditions—as well as emerging practices to mitigate these challenges.

## Typical mining and processing techniques for battery minerals

In Australia, lithium is extracted through hard-rock mining, in which ores rich in lithium (e.g., spodumene) are mined, crushed, and treated at high temperatures (1000 °C or 1832 °F). After cooling, the material is pulverized and treated with sulfuric acid to extract lithium in the form of lithium sulfate; this compound is then refined into high-purity $Li_2CO_3$ or LiOH, which can be used in EV lithium-ion battery production (Fosu et al., 2020; MIT Climate Portal, 2024; Piedmont Lithium, n.d.; Saltworks, 2023).

In countries like Argentina, Bolivia, and Chile, lithium compounds are more commonly extracted from brine, a solution containing dissolved lithium salts found in underground aquifers or in above-ground salt flats. The first step in producing lithium from brine consists of pumping the brine to the surface into evaporation ponds, where it sits for months until enough water evaporates to reach the desired concentration. From there, the lithium solution is pumped to a recovery facility for processing, where it typically undergoes pretreatment to remove contaminants, chemical treatment to isolate the lithium salts, filtration to separate the lithium salts from other products, and treatment with reagent to obtain the final product of $Li_2CO_3$ or LiOH. Once the lithium salt extraction is complete, the remaining brine is typically returned underground (International Lithium Association, 2023; MIT Climate Portal, 2024; Saltworks, 2023).

On the other hand, cobalt is often mined as a byproduct of copper and nickel mining. The minerals are extracted either from deposits (i.e., open-pit mining using trucks and conveyor machines to transport the ore) or underground, where miners use shafts and tunnels to access and extract the ore. The next step is crushing and grinding the ore to prepare it for hydrometallurgical processing, where it undergoes acid leaching under high temperatures (695–705 °C or 1283–1301 °F) and pressure to separate the cobalt from the nickel and copper byproducts in the ore to achieve a high-purity cobalt-sulfate intermediate product suitable for EV battery manufacturing (Cobalt Institute, n.d.; Crundwell et al., 2011).

## Energy sourcing for mining and processing

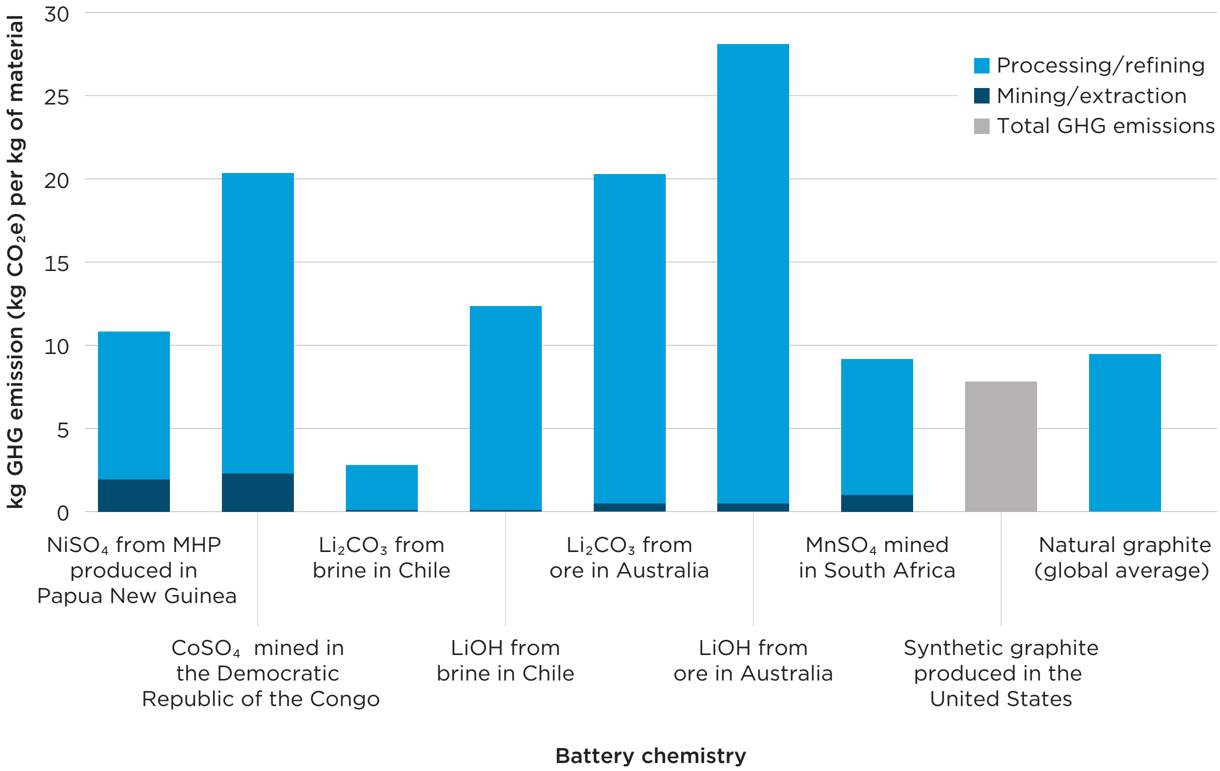
For the operations described above, large amounts of electricity are often used to power mechanical processes (e.g., drilling, grinding, and crushing), as well as to power ventilation in underground mining, dewatering pumps, conveyors belts that transport the ores to the surface, and chemical refining operations such as electrowinning for cobalt. Meanwhile, fossil fuels (often diesel) are typically used to power vehicles in and around the mines and to enable high temperature pyrometallurgical processes like smelting and roasting, typically with coal, natural gas, or fuel oil (Igogo et al., 2021; Wang et al., 2024).

As of 2024, 75% of the mining and over 95% of the processing of natural graphite globally took place in China. In addition to producing 74% of the global supply chain for synthetic graphite, China also processes more than 50% of the global supply of lithium and 75% of the supply of cobalt. Given that China's average grid electricity mix is mostly based on coal, this has implications for the GHG emissions associated with the production of batteries (IEA, 2024b). As discussed in the subsequent section, mining and processing minerals with lower-carbon energy could effectively reduce the carbon footprint of EV batteries.

### Greenhouse gas emissions associated with battery minerals

The production methods and energy sources described above directly determine the carbon intensity of battery minerals. Figure 3 provides a baseline inventory of the carbon intensity of selected intermediate materials used in EV batteries, with analysis based on the R&D GREET 2024 model developed by Argonne National Laboratory (Wang et al., 2024). The figure shows the GHG emissions associated with producing a kilogram of refined nickel sulfate ($NiSO_4$), cobalt sulfate ($CoSO_4$), $Li_2CO_3$ and LiOH, manganese sulfate, and graphite (synthetic and natural). In addition to distinguishing between $Li_2CO_3$ and LiOH, the figure specifies whether these lithium compounds are sourced from brine deposits in Chile or hard rock in Australia. Although Figure 3 presents different lithium sources, only one is needed to produce a battery.

**Figure 3.** Embedded emissions by mass allocation of selected intermediate materials for EV batteries




*Note:* $NiSO_4$ = nickel sulfate; MHP = mixed hydroxide precipitate; $CoSO_4$ = cobalt sulfate; $Li_2CO_3$ = lithium carbonate; LiOH = lithium hydroxide; $MnSO_4$ = manganese sulfate.

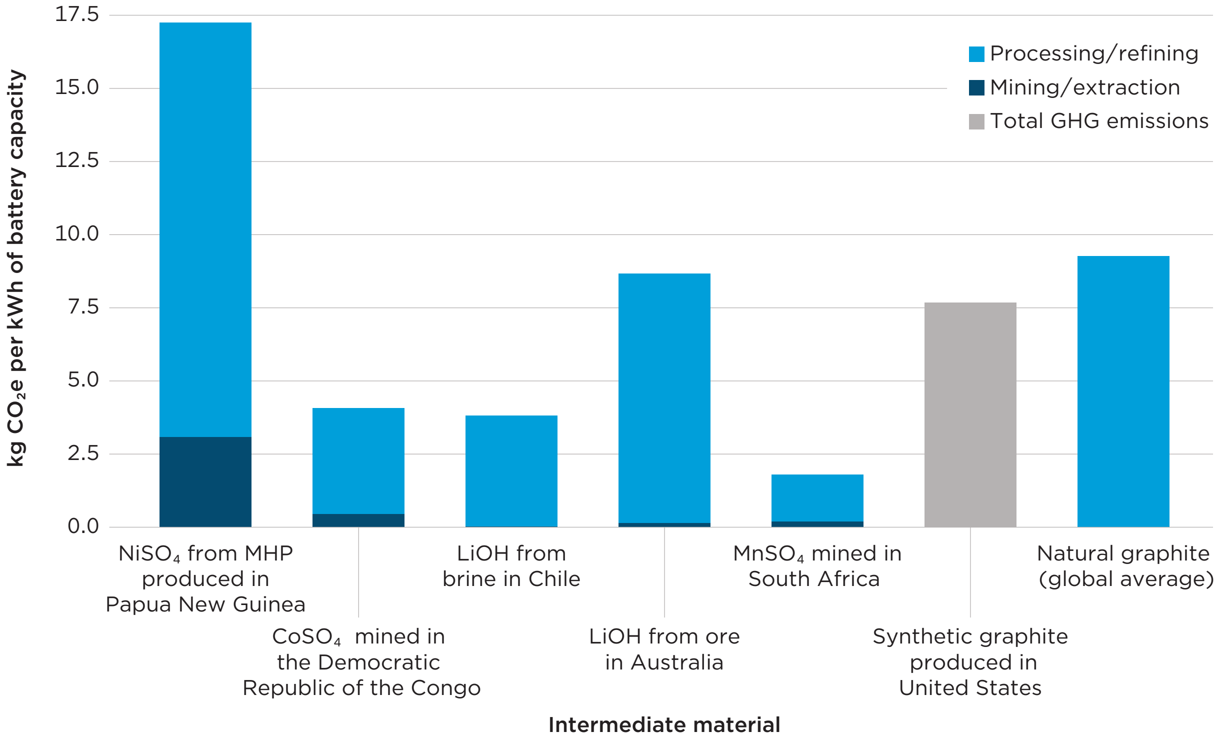
As shown in Figure 3, LiOH and $Li_2CO_3$ derived from hard-rock ores in Australia are estimated to have the highest emissions per kilogram, primarily from processing activities. However, when produced from brines in Chile, both LiOH and $Li_2CO_3$ have substantially lower emissions due to the use of solar evaporation rather than fossil fuel-intensive processing. The production of $CoSO_4$ derived from cobalt-, nickel-, and copper-containing ores mined in the Democratic Republic of the Congo also rank among the highest GHG-emission intensities per kilogram out of the materials presented in Figure 3. By comparison, $NiSO_4$ from ores mined in Papua New Guinea is estimated to rank in the mid-range for emissions intensity. Note that despite the region of mining, the values for nickel, cobalt, and manganese sulfate shown in Figure 3 assume that the processing of the minerals mainly happens in China; this is consistent with the assumptions in R&D GREET 2024 and is also reflected throughout this report.

Synthetic graphite is the predominant form used in EV battery manufacturing (Benchmark Mineral Intelligence, 2022). When produced in the United States, the emissions intensity of synthetic graphite falls close to the mid-range. However, it is important to note that China controls roughly three quarters of the global synthetic graphite supply (as of 2023) and its emissions profile may differ from the United States due to different energy sources (i.e., a high share of coal-powered electricity) and production methods (Benchmark Mineral Intelligence, 2023).

Many of these materials, particularly $CoSO_4$, $NiSO_4$, and copper, are derived from mixed ores that are refined to create multiple products. Thus, the emissions associated with the mining and processing of these ores must be proportionately allocated to the different products and byproducts.[4] The values displayed in Figure 3 are based on allocation by mass. Applying an economic allocation would result in different emission profiles (e.g., an increase by a factor of 4 to 5 for cobalt).

Figure 4 builds on Figure 3 by showing the GHG emission contribution of each intermediate material per kWh of a NMC811 battery, one of the most widely used battery chemistries as of 2024 (IEA, 2025). The mass of each material per kWh of battery was derived based on the assumptions for the R&D GREET model (Wang et al., 2024). Figure 4 only shows emissions associated with selected active battery materials.[5] As such, the total carbon footprint of a battery is greater than the sum of the selected minerals shown in this chart.

**Figure 4.** Carbon intensity of selected intermediate materials in an 84 kWh NMC811 battery




*Note:* $NiSO_4$ = nickel sulfate; MHP= mixed hydroxide precipitate; $CoSO_4$ = cobalt sulfate; $Li_2CO_3$ = lithium carbonate; LiOH = lithium hydroxide; $MnSO_4$ = manganese sulfate.

Figure 4 shows that, among the materials analyzed, $NiSO_4$ typically contributes the most to the carbon footprint of an NMC battery, followed by LiOH—if sourced from Australian ores—and graphite (natural or synthetic). It also highlights that more than half of the emissions associated with LiOH can be avoided if the lithium is sourced from Chilean brines rather than from Australian hard-rock deposits. Overall, Figure 4 suggests that concentrating on reducing emissions during the mining and refining of $NiSO_4$ and the production of graphite and shifting to brine-sourced lithium

4 Emission allocation is typically done either on the basis of mass (e.g., a mineral that accounted for 60% of the total mass of the end products would be assigned 60% of the emissions) or on the basis of value, reflecting their greater economic significance (e.g., a mineral that accounted for 60% of the total revenue from selling the end products would be assigned 60% of the emissions; International Organization for Standardization, 2006/2022).

5 The analysis excluded emissions from other materials used in the battery (e.g., copper and aluminum, used for the current collectors, or battery-pack materials, such as separators), from the midstream production steps (i.e., cathode and anode production and cell manufacturing), or from the battery assembly by manufacturers.

(where supply is available) could be promising opportunities to reduce the carbon footprint of NMC811 batteries.

## Environmental and social impacts of mineral mining

Beyond GHG emissions, mining and processing operations also carry broader environmental and social consequences. Mineral supply chains, including for EV batteries, have traditionally been characterized as opaque, reflecting their inherent complexity, company secrecy, limited or nonextant regulatory frameworks, and technological limitations (Budler et al., 2024; Montecchi et al., 2021; Schäfer, 2023). A 2016 Amnesty International report chronicled issues connected to EV batteries, revealing hazardous conditions for artisanal miners, including children, working in the cobalt mines of the Democratic Republic of the Congo. Documented problems included miners working without protective equipment and women working 10 hours per day for around US$1.50 (Amnesty International, 2016).

Mining and processing of battery minerals is also connected to environmental issues like depletion of water resources, degradation of land and biodiversity, and generation of toxic waste, among others. In Argentina, Bolivia, and Chile, which have some of the largest lithium brine reserves in the world, large amounts of water are typically required to produce $Li_2CO_3$ or LiOH (Ellerbeck, 2023). In Chile, it is estimated that anywhere between 170 and 7,660 liters of water are required to produce a kilogram of $Li_2CO_3$, depending on the concentration of lithium in the brine (Mas-Fons et al., 2024). This can represent a significant challenge for regions already facing severe water stress, and the extraction of large quantities of brine can potentially affect freshwater resources (Lakshman 2024; World Economic Forum, 2023; World Resources Institute, n.d). The extraction of lithium can thus exacerbate water scarcity, affecting the livelihoods of local communities.

Several mining companies are exploring techniques for more sustainable lithium extraction, including direct lithium extraction (DLE), whereby chemical, adsorptive, or membrane-based processes are used to selectively extract lithium from brine sources, reducing water consumption, land use, and production time. In 2024, for example, Eramet in Argentina started commercial-scale operations at a DLE plant that can produce 24,000 metric tons of battery-grade $Li_2CO_3$ annually (Benchmark Mineral Intelligence, 2024a). The project also aims to recycle 60% of the water used in the processes. However, the environmental benefits of DLE should be carefully evaluated on a site-specific basis, as water consumption can vary significantly depending on the extraction technology employed and the local hydrogeological conditions. Some configurations may result in higher water use compared with traditional brine or ore-based lithium production methods (International Lithium Association, 2024; Naimark, 2023).

Additionally, mining activities are often located in areas with fragile ecosystems. It is important for mining companies to ensure that mining practices promote biodiversity conservation. This includes minimizing the opening of new mines, not seeking permits to develop new mine activities in designated protected areas, restoring soil and vegetation in areas that have been mined, and properly managing mining waste through measures such as dry-stack tailing (reducing water content in the waste slurry so that it can be stacked) to reduce the risk of ground water contamination and failure of conventional dam storage (Earthworks, n.d.; International Council on Mining and Metals [ICMM], n.d.; IEA, 2022).

The environmental and social challenges described above—from labor conditions to water use to biodiversity impacts—have increasingly become the focus of environmental, social, and governance

(ESG) frameworks within the mining sector. Facing pressure from consumers, regulators, and advocacy groups, the mining industry is progressively incorporating ESG standards into production practices. Before examining technological and policy solutions, it is important to assess the extent to which voluntary industry initiatives have addressed these concerns and where gaps remain.

## Overview of ESG principles in the mining sector

Consumers have become increasingly conscious of the origins of raw materials used in their products, with many opting for products made in accordance with ethical and sustainable practices (Frey et al., 2023; Kraft et al., 2019). However, as evidenced in the 2022 *Responsible Mining Index* (RMI), much remains to be done for mining companies and mining sites across the world to more substantially embrace ESG principles. Indeed, the mining site assessments revealed that 94% of the 250 assessed mine sites operating across 53 countries lacked evidence of engaging with local communities and workers on ESG-related issues—such as environmental impacts, safety concerns, or grievances—despite having ESG commitments or announcements.

The RMI assessment of mining companies revealed an average score improvement of 11% for the 37 companies that were assessed in 2020 and 2022. These improvements mostly came from lagging companies catching up on implementing ESG policies. By contrast, companies outside of the bottom tier recorded slower rates of improvement, registering an average increase of 8% between 2020 and 2022, suggesting a potential plateau in the advancement of responsible mining practices (RMI, 2022). The report also identified examples of good practices in those areas where many companies performed poorly, including climate change, life-cycle management, working conditions, gender inequalities, and community wellbeing. For example, Anglo American has put comprehensive rules in place with regard to life-cycle management (RMI, 2022).[6]

Specific to EV batteries, a 2024 Amnesty International report evaluated the human rights due diligence reporting of 13 major EV manufacturers regarding the sourcing of cobalt, copper, lithium, and nickel for battery production (Amnesty International, 2024). The assessment was based on six criteria: human rights policies, risk assessment, impact mitigation, monitoring, transparency, and remediation. Overall, Amnesty International noted that relative to its 2017 assessment, the 2024 results indicated that automakers have made improvements in introducing due diligence policies. Nonetheless, there is room for more improvement, and performance across different automakers varied greatly. Top 2024 performers included Mercedes-Benz (with an assessment score of 51 out of 90), Tesla (49), and Stellantis (42). By contrast, Hyundai received a score of 21, Mitsubishi 13, and BYD just 11, suggesting minimal transparency or supply chain accountability among these lowest-ranked companies. The report emphasized the urgent need for EV companies to enhance transparency, conduct comprehensive supply chain mapping, engage meaningfully with affected communities, and implement robust safeguards against human rights abuses in mineral sourcing.

These findings from Amnesty International are in alignment with those of Lead the Charge, a network of global civil society organizations pushing for automakers to revamp their supply chains to become fossil free, sustainable, and respectful of the rights of Indigenous Peoples, workers, and local communities (Lead the Charge, 2025). In 2025, the organization published the findings of their third *Lead the Charge Leaderboard* report, which assessed 18 of the largest EV automakers globally

6 This category evaluates how effectively companies integrate long-term economic, environmental, social, and governance considerations throughout a mine's lifespan, ensuring sustainable outcomes for local communities and workers after closure.

against 80 indicators to determine their progress toward more equitable, sustainable, and fossil-free supply chains. The assessment found that, overall, the automakers had made some progress, with an average increase of 3% compared with the 2024 assessment. Most improvements pertained to climate and human rights, where scores increased by 8%, followed by responsible mineral sourcing, where the average score increased by 5%. The report attributed these improvements to recently approved regulations like the EU's Batteries Regulation and Corporate Sustainable Due Diligence Directive, showcasing the importance of legally binding regulations for ESG-related accountability. Despite these encouraging signs, none of the 18 automakers recorded an overall score above 50%. The top performing automakers were Tesla (43%), Ford (42%), and Mercedes (41%), while the lowest scorers were BYD (6%), GAC (4%), and SAIC (1%).

Independent third-party ESG assessments, such as those conducted by the Initiative for Responsible Mining Assurance (IRMA), can provide mining companies and automakers with credible, standardized benchmarks to evaluate and improve their environmental and social performance at the mine-site level. By offering transparent audits across a wide range of robust criteria, these assessments help companies identify gaps and define pathways to address those gaps. In return, this can help build trust with stakeholders and demonstrate progress toward responsible sourcing. For automakers, sourcing from mines audited against credible standards can support supply chain alignment with ESG commitments, alleviating concerns from regulators, investors, and consumers (IRMA, n.d.).

Widespread challenges persist in effectively implementing ESG principles across the mining sector and automotive supply chains. However, emerging success stories around the world demonstrate that responsible mining practices are feasible and offer a template for how to scale these practices with additional support from governments and businesses. Table 1 highlights several leading efforts in responsible mining from across the globe.

**Table 1.** Examples of mining companies' efforts to adhere to environmental, social, and governance principles

| Country | ESG implementation | Mineral of focus | Source |
|---|---|---|---|
| **Australia** | Through a grant from the Australian government, Albemarle's lithium hydroxide refinery is investigating methods to convert mining waste tailings into new products for industries like transport and construction. | **Lithium** | Australian Government, Department of Industry, Science and Resources (2023) |
| **Canada** | Vale's Long Harbor facility in Newfoundland and Labrador produces Class 1 high-purity nickel with a carbon footprint of 6.2 metric tons of $CO_2$ per metric ton of material produced. Since its inception in 2014, the Long Harbor refinery has employed hydrometallurgical instead of pyrometallurgical processing of nickel ores, eliminating the need for smelters and smokestacks. This approach not only reduces GHG emissions and operating costs but also improves the recovery rates of valuable byproducts such as cobalt. | **Nickel, cobalt** | Vale (n.d.); Natural Resources Canada (2025) |
| **Chile** | In August 2021, BHP began powering its Escondida and Spence copper mines in Chile entirely with renewable energy through purchase power agreements[a] with Enel Generación Chile and Colbún. The shift toward 100% renewables aims to replace coal-based electricity and is expected to cut more than 3 million metric tons of $CO_2$ emissions annually from 2022, which the company claims is comparable to removing about 700,000 cars from the roads. | **Copper** | BHP Group (2021) |
| **Democratic Republic of the Congo** | In early 2024, Tenke Fungurume became the first mine in Africa and the first mine owned by a Chinese company globally to receive the Copper Mark certification, an assurance framework that promotes responsible production for nickel, among other minerals, through independent third-party evaluations of legal compliance, labor relations, environmental management, and more. Furthermore, the site began an independent assessment against the IRMA standard in June 2025. | **Nickel** | CMOC Group Ltd. (2024) |
| **Mozambique** | In December 2024, Syrah Resources' Balama graphite mine in Mozambique became the first graphite operation to complete an IRMA audit. The evaluation covered social and environmental responsibility, business integrity, and legacy planning. The mining company was assessed on over 400 ESG criteria and achieved a rating of 50, meaning that the companies met all critical requirements and at least 50% of key ESG criteria. | **Graphite** | IRMA (2024) |

*Note:* Some of the examples provided are based on industry claims and have not been independently verified by the ICCT.

[a] Under purchase power agreements, renewable energy facilities may not be located on the mining site; decentralized producers can generate the electricity off-site and attribute it to the mining operation.

# Technologies and techniques for lower-carbon batteries

Realizing the ESG frameworks and industry-led initiatives described above will require the widespread adoption of new, more sustainable mining and battery manufacturing processes. This section examines technological and operational innovations that can reduce the environmental footprint of battery production, providing concrete pathways for achieving more sustainable outcomes across the supply chain.

The previous review of battery mineral supply chains and their associated emissions—along with the ESG challenges discussed in the previous section—suggests that, while EVs already have much lower life-cycle emissions than comparable ICEVs, there are numerous opportunities to further reduce the GHG emissions and other harms associated with EV battery production. This section will examine several of these opportunities, including transitioning to renewable energy, switching to less carbon-intensive chemistries, and using more recycled minerals. We also offer a quantitative analysis of the projected impacts of these initiatives.

## Renewable energy in mineral extraction and processing

The transition toward clean energy in the mining sector is at an early stage but shows potential for growth. A study conducted by the U.S. Department of Energy estimated that the installed capacity of renewable energy in the mining sector increased from 42 MW in 2008 to 3,397 MW in 2019, highlighting the feasibility and scalability of renewable energy in mining applications despite the large reliance on hybrid systems (i.e., renewable energy backed by fossil fuels) in 2018 and 2019 (Igogo et al., 2021).

In Chile in 2019, mining company BHP signed 15-year power agreements to supply its coal-based Escondida and Spence copper mines with 100% renewables such as wind and solar. BHP estimated that this will reduce the $CO_2$ produced per year by 3 million tons compared with 2020 levels while reducing operational costs by 20% (BHP Group 2019, 2021). In 2022 and 2023, the company achieved 100% renewable electricity use in its two Chilean mines (BHP Group, 2024). Considering that energy is one of the biggest expenses of mining companies—representing up to 30% of their operating costs—the declining cost of renewable energy also presents an opportunity to significantly reduce operating costs alongside emissions (Deloitte, 2017).

Pouresmaieli et al. (2023) performed a strengths, weaknesses, opportunities, and threats (SWOT) analysis to assess the suitability of renewable energy in comparison to fossil energy sources. The analysis concluded that the strengths and opportunities—including job creation, reduced GHG emissions, and reduced cost of mining operations—outweigh the weaknesses and threats, such as lack of skilled labor to operate and maintain renewable systems, high upfront and maintenance costs, and uncertainties about renewable energy supply. However, for some functions already using electricity (e.g., vehicles, ventilation, and pumps), it is currently more technologically feasible and cost-effective to switch to renewable electricity than it is for other fossil-fuel based functions (e.g., high-temperature or high-pressure chemical processing).

Furthermore, Pouresmaieli et al. (2023) formulated several strategies and recommendations for governments to support the integration of renewable energy systems in mining operations. These included introducing or modernizing mining regulations to favor integrations of renewables in the medium term as well as training and educating mine operators in renewable energy technologies and their advantages. Governments are also encouraged to provide financial incentives—such as low-interest loans or tax exemptions—to support mine operators in adopting renewable technologies. Finally, the study recommended establishing regulations that enable mine operators to resell surplus renewable electricity produced on-site to generate additional revenue.

To address the intermittency of solar and wind energy (or to accommodate mines in off-grid areas), battery energy storage systems can enable continuous operations. In Australia, for example, the copper and gold mining company Sandfire added a solar-powered energy storage system capable of providing 6 MW of power alongside its 19 MW diesel-fired power station. As a result, 20% of annual power comes from solar energy and the company has reduced its $CO_2$ emissions by 12,000 tons annually (Sandfire, n.d.).

In China, renewable energy could play a growing role in mining and processing activities. Several anode manufacturers have moved their activities to the Sichuan region, where they can leverage the area's abundant hydropower energy resources (Benchmark Mineral Intelligence, 2022). In April 2024, the Chinese government issued a notice mandating that all regions develop technology innovation roadmaps to guide the construction of "green mines"[7] across newly built, expanded, or renovated production sites. The policy aims for 90% of licensed large-scale mines and 80% of licensed medium-sized mines to comply with the national green mine standard by the end of 2028. Local authorities are also encouraged to support small-scale mines in adopting these standards in accordance with local conditions. To help accelerate the transition, the initiative is backed by a suite of financial-support mechanisms, including tax deductions and green credits (China Ministry of Natural Resources et al., 2024).

Similarly, in California, efforts are underway to scale up extraction of lithium from brine as part of existing and new geothermal power production near the Salton Sea. This region is home to substantial lithium resources,[8] potentially positioning the state as a major supplier of low-emissions lithium domestically and beyond (Dobson et al., 2023).

In summary, projects around the world demonstrate how mining and processing operations can be powered by clean energy sources that result in cleaner EV batteries and lower operating costs for mines and mineral processing companies. Further opportunities to enhance sustainability of EV batteries include transitioning toward cleaner vehicles and machineries, as discussed in the following subsection.

## Zero-emission vehicles and machinery

Mining vehicles and equipment, such as trucks, loader tractors, haulage cranes, or excavators, are traditionally powered by diesel and therefore produce GHGs, particulate matter, noise, and heat, all of which compromise the health of mine workers (Hooli & Halim, 2025; ICMM, n.d.). The shift toward ZEVs and zero-emission machinery therefore provides an opportunity to improve the working conditions of miners, especially in underground mining settings. Several technological readiness studies suggest that electrified mining vehicles and machinery provide similar productivity when

7 According to the Ministry of Natural Resources et al. (2024), a green mine is one that, throughout the entire process of mineral resource development, implements scientific extraction methods; keeps disturbances to the ecological environment within a controllable range; and implements ecological restoration, efficient resource utilization, standardized enterprise management, production safety, and harmonious mining-local community relations.

8 The region is estimated to contain 4 million metric tons of lithium carbonate equivalent (LCE) of proven lithium resources and 18 million metric tons of LCE of probable lithium resource (Dobson et al., 2023).

compared with their diesel counterparts (Acuña-Duhart et al., 2024; Hooli et al., 2024; McGuire et al., 2022).

The transition toward electrified vehicles and machinery in underground mining is gaining momentum, with at least 53 mines having adopted or trialed battery EVs as of 2024, mostly in North America (Hooli & Halim, 2025). Electrification via overhead wires (i.e., a trolley system) is already a mature technology for mining trucks, typically in a hybrid configuration with a diesel engine; the use of this technology helps to reduce air pollution and fuel costs while providing greater power for heavy loads on steep routes (Digging Deep, 2023; International Mining, 2024). Lessons learned from these mines will help to identify best practices and develop the knowledge to address the challenges and concerns the mining industry currently faces, including training workers on operating and maintaining electrified equipment, minimizing fire risks from battery EVs operated underground, identifying best charging strategies to maximize productivity (e.g., direct-current fast charging vs. battery swapping), and optimizing the design of mines to facilitate operational logistics (Hooli & Halim, 2025).

## Optimizing battery design and manufacturing

Since its commercialization in the early 1990s, the lithium-ion battery has undergone numerous innovations leading to improved energy density and durability. The following subsections detail how these technological innovations impact the carbon footprint of EV batteries.

### Existing literature on the carbon intensity of battery chemistries

Numerous LCA studies on lithium-ion batteries have sought to determine how different chemistries influence a battery's carbon footprint. These studies vary in terms of their scope, the battery chemistries analyzed, and the region of manufacture; accordingly, there are different carbon intensities associated with different EV batteries. Table 2 lists the locations and chemistries considered by these studies and summarizes their key findings.

**Table 2.** Summary of selected studies on the carbon intensity of different lithium-ion battery chemistries

| Study | Region(s) | Chemistry | Key findings |
|---|---|---|---|
| **Xu et al. (2022)** | China, the EU, United States | Lithium iron phosphate (LFP), nickel cobalt aluminum (NCA), and multiple nickel manganese cobalt (NMC) variants | Cathode, anode, and cell production account for 74%–83% of GHG emissions for LFP cells and for 54%–69% of GHG emissions for NMC/NCA cells<br><br>With increased integration of renewable energy, the proportion of GHG emissions associated with cathode, anode, and cell production could decrease to 39%–76% for LFP and 23%–61% for NMC/NCA<br><br>LFP batteries have the lowest carbon footprint across all regions considered<br><br>Batteries produced in Europe have lower GHG emissions than those from China or the United States due to cleaner energy mix |
| **Winjobi et al. (2022)** | United States, China, Japan, South Korea, Europe | NMC111, NMC532, NMC622, NMC811[a] | NMC batteries with higher nickel content have lower GHG emissions than those with lower nickel content on a per-kWh basis (e.g., production of NMC 811 yields 7.5% lower GHG emissions compared with NMC111)<br><br>NMC produced in regions with lower-carbon electricity grids (e.g., Europe and the United States) yield lower GHG emissions than regions with more carbon-intensive grid electricity (e.g., Japan and South Korea)<br><br>Raising the specific energy of NMC batteries by increasing nickel content reduces the amount of material needed for the cathode production on a per kWh basis, thereby also reducing GHG emissions |
| **Transport & Environment (2022)** | Europe | LFP, NMC811, solid-state batteries (SSBs) | SSBs with solid oxide electrolyte and NMC811 cathodes have a 24% lower warming potential than liquid electrolyte NMC811<br><br>SSBs with LFP cathodes have 11% higher GHG emission per kWh than SSBs with NMC811 cathodes due to lower energy density<br><br>SSBs with LFP cathodes still provide a 2% GHG reduction versus advanced lithium-ion LFP<br><br>Sustainable lithium sourcing is critical because SSBs require 35% more lithium per kWh<br><br>With sustainable extraction, SSBs could have a 39% lower GHG footprint versus advanced conventional NMC811 |
| **Degen et al. (2024)** | Not specified | *Prospective batteries:*<br><br>LFP, solid-state (NMC 900 – SSB),<br><br>Sodium nickel iron manganese, sodium-ion battery (SIB)<br><br>(NaNFM 422 – SSB)<br><br>*Conventional batteries:*<br><br>NCA, NMC532, NMC622, NMC811, NMC900 | SSBs (88–130 kg $CO_2$e/kWh) and SIBs (75–87 kg $CO_2$e/kWh) have higher emissions than conventional lithium-ion battery (58–92 kg $CO_2$e/kWh)<br><br>Advanced LFP and NMC900 cells are the most sustainable lithium-ion options in terms of emissions<br><br>Optimizing their design (e.g., thinner current collectors) and production could reduce environmental impact by up to 38% for LFP and 22% for the NMC900<br><br>Carbon emissions of all chemistries studied are higher per kWh when the cell is in a high-power configuration versus a high-energy configuration |
| **Guo et al. (2023)** | Not specified | LFP, SIB | SIB cathodes have higher carbon emissions than LFP<br><br>SIB cathodes produce ~60 kg $CO_2$e/kWh versus 40 kg $CO_2$e/kWh for LFP cathodes<br><br>Future advances could reduce SIB carbon footprint, including lower-carbon materials, improved cathode synthesis, hydrometallurgical recycling, low-carbon electricity, and economies of scale |

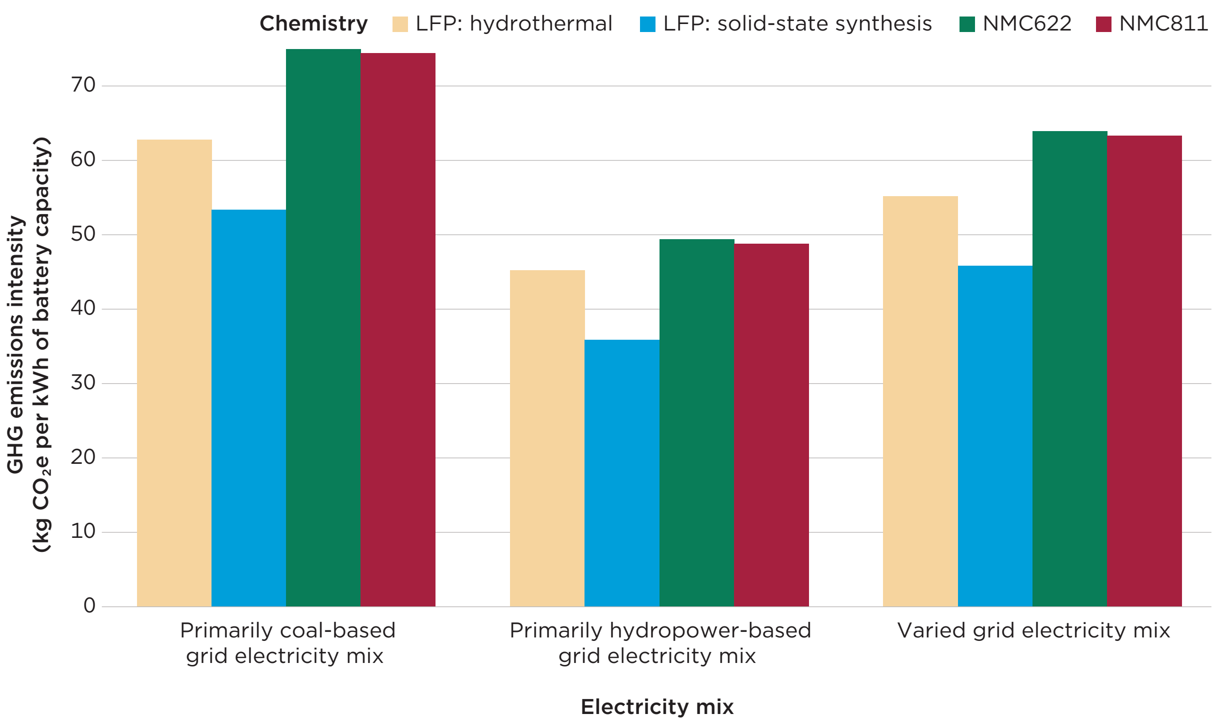
[a] The numbers associated with each type of NMC battery represent the ratio of nickel (N), manganese (M), and cobalt (C) contained in the NMC cathode material. Thus, an NMC111 contains equivalent amounts of nickel, manganese, and cobalt. As such, a NMC811 cathode contains a higher proportion of nickel content than the NMC 532, while containing proportionately less manganese and cobalt.

As shown in Table 2, there is little consensus about the relative carbon intensity of different EV battery chemistries, with the differences largely attributable to the data and carbon intensity assumptions used for material sourcing. Several studies, though not all, found that LFP batteries have lower emissions per kWh when compared with NMC or NCA batteries due to the lower energy requirement for cathode production and minerals processing. The studies all indicated that cathode, anode, and cell production account for a large majority of emissions associated with lithium-ion battery production, regardless of chemistry; these studies also showed that batteries produced in regions with cleaner electricity (e.g., Norway and Sweden) typically have significantly lower emissions compared with batteries produced in countries that have more carbon-intensive grids (e.g., the United States or China). Degen et al. (2024) and Guo et al. (2023) estimated that the carbon footprint of solid-state batteries (SSBs) produced as of 2023 is higher than current LFP or NMC batteries. On the other hand, Transport & Environment (2022) estimated that SSBs have lower emissions compared with conventional LFP and NMC chemistries.

## Comparative analysis of batteries chemistries

Building on these findings, we compared cradle-to-gate GHG emissions for three battery chemistries—LFP (solid-state and hydrothermal synthesis), NMC622, and NMC811—across three different electricity grid scenarios: a primarily hydropower-based mix (equivalent to Norway's average mix in 2023), a primarily coal-based mix (similar to China in 2022), and a more varied electricity mix (similar to the United States in 2023). The analysis used the R&D GREET 2024 model, selected for its open-source accessibility and transparent data source documentation.[9] The analysis focused on battery electric passenger cars with an 84 kWh battery. The results are presented in Figure 5.

**Figure 5.** Life-cycle analysis of LFP and NMC batteries across different grid electricity mix scenarios




9 The R&D GREET model is one of several available life-cycle inventory models. Consequently, the findings presented here may differ from those of other studies. Data on the grid electricity mixes for the three regions were obtained from the IEA (n.d.). These data reflect national average grid electricity mixes, but mining and manufacturing operations often rely on local energy sources that may differ significantly in carbon intensity. Therefore, the carbon intensity of individual operations may vary.

Figure 5 illustrates how chemistry, material processing pathways, and region of production impact the carbon intensity of EV batteries. Batteries produced using a more coal-heavy electricity mix show an average carbon intensity that is about 48% higher across all chemistries than those produced through a hydropower-based electricity mix. Batteries produced with a varied electricity grid (i.e., a more balanced mix of renewable and fossil fuel energy sources) showed intermediate carbon intensities. LFP chemistries generally have carbon intensities comparable to or lower than NMC chemistries within the same region. Among the LFP material processing routes, the solid-state pathway delivered lower GHG emissions.

The results also showed that the NMC622 and the NMC811 chemistries have similar GHG emission footprints and tend to be more carbon intensive than LFP. This is attributable to the higher energy use for minerals processing, particularly for nickel and cobalt. At the same time, the regional electricity mix has a large influence on the carbon footprint of the battery: the most carbon-intensive chemistry produced with low-carbon electricity had lower emissions than the least carbon-intensive chemistry produced with high-carbon electricity.

### Prospective impact of recycling on battery carbon footprint

While most batteries today are produced mainly with virgin minerals, recycled materials may play a growing role in the coming decades as more batteries reach the end of life (Tankou et al., 2023). Since the recovery of minerals from used batteries generates GHG emissions, it is important to assess how these emissions compare with those from the production of virgin materials. Therefore, we evaluated the impact of using recycled rather than virgin minerals on the carbon footprint of newly manufactured batteries using the R&D GREET 2024 model.

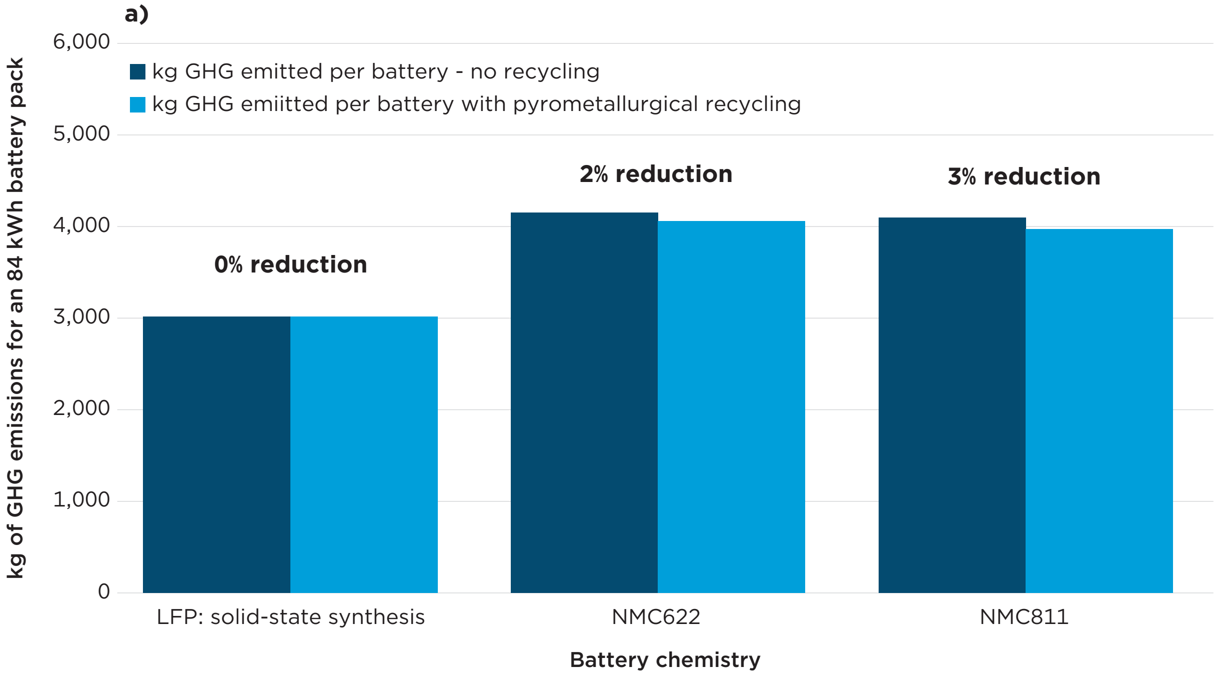
We considered two recycling pathways: pyrometallurgical processing and hydrometallurgical processing.[10] To represent a future scenario in which recycling technologies have matured and widely scaled, our analysis assumed that the recycled share of metals matches recovery targets for 2027 through 2031 set by the EU's Batteries Regulation (90% for cobalt and nickel and 50% for lithium; Regulation [EU] 2023/1542).[11] We conducted the analysis using the "primarily hydropower" scenario introduced in Figure 5 (representative of Norway's average electricity mixes in 2023).[12] The results are presented in Figure 6.

10 Pyrometallurgical processing recovers metals (e.g., cobalt, nickel, manganese) from batteries using high-temperature smelting, while hydrometallurgical processing recovers battery metals through acid leaching and solvent extraction (Tankou et al., 2023).

11 Because lithium is not typically recovered from pyrometallurgy (Tankou et al., 2023), we do not model the 50% lithium recover target for this recycling pathway.

12 These results reflect the impact of low-carbon electricity mixes on embedded GHG emissions of battery recycling. Results would differ in regions with higher-carbon electricity sources.

**Figure 6.** Impact of (a) pyrometallurgical and (b) hydrometallurgical recycled material on the carbon footprint of LFP, NMC622, and NMC811 batteries manufactured in Norway



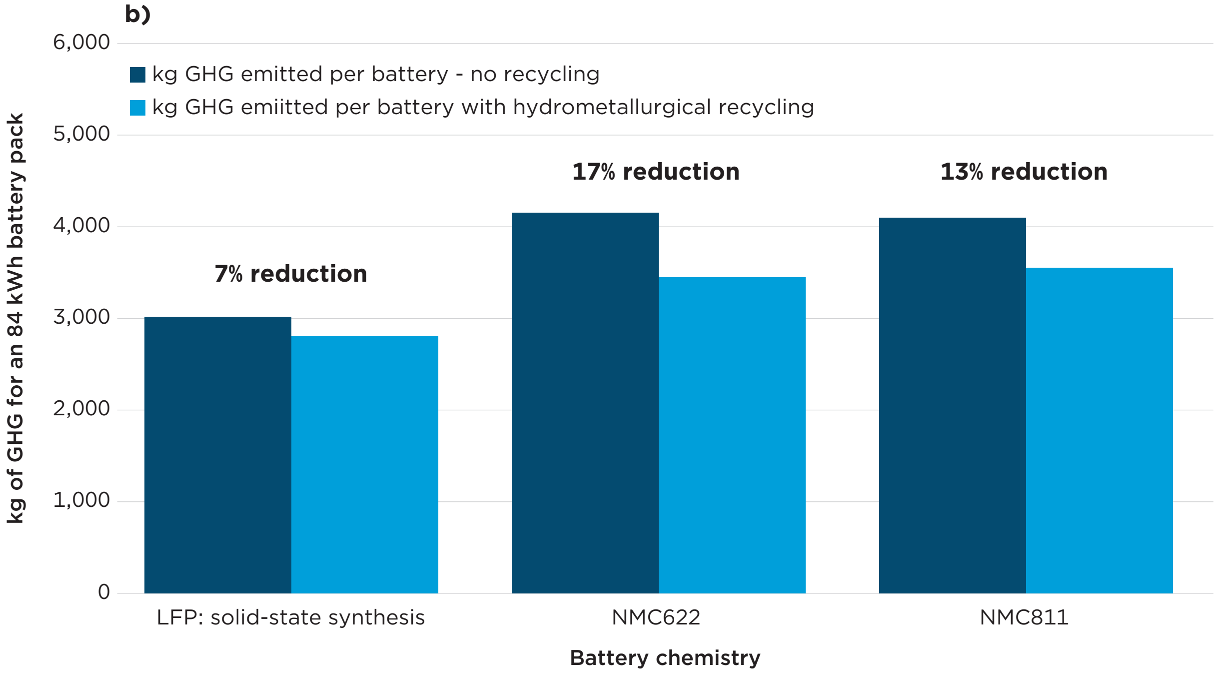




Figure 6a illustrates that applying pyrometallurgical recycled material in the manufacturing of new NMC622 and NMC811 batteries led to moderate reductions in total GHG emissions—approximately 2% and 3%, respectively. These reductions were mainly connected to the recovery of nickel and cobalt, which offset the need for the more carbon-intensive virgin production of these minerals. In the case of LFP (solid-state synthesis), there was virtually no reduction in GHG emissions, mainly because lithium was not recovered and other valuable minerals that could be recovered (e.g., cobalt or nickel) were not present.

Figure 6b shows that use of hydrometallurgical recycled materials offers greater emissions reductions for newly built NMC batteries. The GHG emissions for NMC622 and NMC811 decreased by 17% and 13%, respectively. This improvement occurred because the hydrometallurgical process is less energy intensive than the virgin production pathway, especially regarding nickel and cobalt. For LFP batteries, hydrometallurgy enabled partial recovery of lithium, resulting in a 7% reduction in carbon footprint by offsetting virgin lithium production. Overall, these findings underscore that while recycling can reduce the carbon footprint of batteries, the magnitude of those benefits depends on the chemistries involved and the recycling pathway employed. If these variables were optimized, our results indicated that GHG emission reductions could approach 20%.

### Improvement in battery durability and battery material substitution

Improvements in battery durability extend the lifespan of EV batteries, therefore reducing pressure on the demand for new mining. Longer lasting batteries also enable second-life applications, such as grid-energy storage systems, potentially further delaying the demand for newly mined resources. Several factors influence battery durability, such as the chemistry of the battery. For example, LFP batteries typically last longer than NMC batteries despite having lower energy density (Evro et al., 2024). Another factor is the design of the battery. For instance, using cell-to-pack configurations—whereby cells are directly assembled into packs without using modules—can improve battery longevity by favoring better heat dissipation (Zhang et al., 2024). The simpler cell-to-pack architecture may also make batteries less prone to technical failures (E-Mobility Engineering, n.d.).

Another approach for more sustainable EV batteries involves replacing EV battery materials with more readily available, less environmentally impactful alternatives. For example, an emerging trend is to incorporate silicon into graphite anodes and even develop fully silicon-based anodes to increase battery energy density (IEA, 2024b; Benchmark Mineral Intelligence, 2024b). When optimized, silicon-based anodes could increase anode capacity by up to 60% compared with traditional graphite anode capacity (Benchmark Mineral Intelligence, 2024b). If sourced through low-emission processes, silicon may also help reduce the carbon footprint of EV batteries—particularly when it displaces synthetic or natural graphite produced with fossil-intensive energy.

## Policy tools for more sustainable and socially responsible batteries

The technological solutions presented in the previous section—from renewable energy in mining to advanced recycling processes—demonstrate what is technically feasible to reduce the environmental impact of battery production. However, adopting these solutions at a sufficient scale and speed requires supportive policy frameworks. This section examines regulatory approaches that governments could employ to accelerate the adoption of sustainable practices and ensure that battery supply chains align with environmental and social responsibility goals.

The growing demand from consumers and governments for sustainable and socially responsible products provides an opportunity for the mining sector to shift away from its traditional reputation as an industry responsible for environmental degradation and human rights abuses toward one that embraces environmentally and socially responsible practices (Amnesty International, 2024). As the demand for mined minerals increases, policies at the national and international levels will be critical for ensuring that the industry makes these improvements. This section examines policy approaches across three levels: (1) international frameworks establishing baseline principles, (2) requirements for battery transparency and circularity, and (3) integration of sustainability criteria into broader vehicle regulations.

## International frameworks for more responsible mining

Several internationally recognized due diligence schemes have been introduced throughout the past decades, taking the form of laws, principles, or guidelines that aim to protect fundamental social and environmental rights. These schemes present processes for governments and private companies to assess adverse impacts of their operations and activities on communities' rights, including access to water and education, adequate living standards, and freedom of speech. Due diligence schemes also call for states and enterprises to establish grievance mechanisms to enable workers and populations affected by their activities to submit complaints and obtain remediation when their rights have been violated (Organisation for Economic Co-operation and Development [OECD], 2018, 2023; Office of the United Nations High Commissioner for Human Rights, 2011). Table 3 describes some of these internationally recognized due diligence schemes.

**Table 3**. Examples of internationally recognized due diligence schemes

| Diligence scheme | Description | Legal status | Source |
|---|---|---|---|
| **UN International Bill of Human Rights** | Includes the International Covenant on Civil and Political Rights (ICCPR) and the International Covenant on Economic, Social, and Cultural Rights (ICESCR), both adopted in 1966. These treaties set the fundamental human rights standards upon which other due diligence schemes have been built (e.g., access to adequate living standards, right to strike, freedom of children from social and economic exploitation). Also included in the bill is the Universal Declaration of Human Rights (UDHR), adopted by the UN General Assembly in 1948; it set out for the first time fundamental rights to be universally accepted and protected by each individual and organ of society. | **ICCPR and ICESCR are binding for countries that have ratified the bill**<br><br>**UDHR is non-binding** | Office of the United Nations High Commissioner for Human Rights (2025a)<br><br>United Nations (1948) |
| **UN Guiding Principles on Business and Human Rights** | These principles outline the responsibility of states, corporations, and businesses to respect human rights, as well as the duty of states to protect access to remedies for victims of business-related abuses. These principles serve as the foundation for corporate due diligence policies worldwide. | **Non-binding (applies broadly to states and businesses)** | Office of the United Nations High Commissioner for Human Rights (2011) |
| **OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected Areas** | Establishes a step-by-step framework for companies sourcing minerals from high-risk areas. It aims to prevent human rights abuses and the financing of conflicts through mineral trade while promoting transparency and ethical sourcing in the mining sector. | **Non-binding** | OECD (2016) |
| **OECD Due Diligence Guidance for Responsible Business Conduct** | Offers practical steps for companies to implement the OECD Guidelines for Multinational Enterprises. It helps businesses identify, prevent, and mitigate adverse impacts related to human rights, labor, governance, and environmental risks in their operations and supply chains. | **Non-binding** | OECD (2018) |
| **OECD Guidelines for Multinational Enterprises** | Provides recommendations for multinational corporations on responsible business practices in areas such as human rights, labor rights, environmental protection, consumer interests, taxation, and anti-corruption. | **Non-binding (governments endorse these guidelines, but compliance is voluntary)** | OECD (2023) |
| **ILO Tripartite Declaration of Principles on Multinational Enterprises & Social Policy** | Developed by governments, employers, and workers, this declaration provides global guidance on corporate responsibility in employment, training, working conditions, industrial relations, and social policies. It is the only global instrument created through a tripartite process. | **Non-binding** | International Labour Organization (2023) |

Because these frameworks are not industry specific, they must be adapted to specific sectors, such as EV battery manufacturing, if they are to have an impact. In recognition of this, the EU, through its Batteries Regulation, will require that all economic operators that produce or sell EV batteries within the EU develop due diligence policies by August 2027 (Council of the European Union, 2025). These policies must align with all internationally recognized due diligence provisions detailed in Table 3; furthermore, these policies must outline the measures that the economic operators will undertake to minimize social and environmental risks associated with their activities. These social and environmental risk categories, detailed under Annex X of the EU Batteries Regulation, include soil pollution, energy waste, biodiversity loss, child labor, and forced labor (Regulation [EU] 2023/1542).

A key concept of responsible mining is the principle of free, prior, and informed consent (FPIC), which acknowledges the rights of affected communities—often Indigenous and tribal groups—over their natural resources and habitats and identifies the responsibility of governments to protect those rights. FPIC recognizes the right of affected communities to give or refute consent for any activities affecting their lands, such as mining. It builds on several legal instruments, including the Declaration on the Rights of Indigenous Peoples (UNDRIP) of 2007, which calls for governments to protect Indigenous peoples' right to FPIC (Office of the United Nations High Commissioner for Human Rights, 2025b).

While some jurisdictions, such as Bolivia, the province of British Columbia, Canada, and the Philippines, have incorporated FPIC into their legal frameworks, FPIC is not a legally binding requirement in most countries (Sellwood et al., 2023). Even where legally recognized, implementation challenges remain. For instance, multiple leadership structures may coexist within specific Indigenous and tribal communities, raising questions about who holds the legitimate authority to grant consent (Sustainability Directory, 2025). There have also been instances of governments ignoring decisions made by Indigenous groups (Sellwood et al., 2023).

## Promoting battery ESG transparency

As consumers become more sensitive to the social and carbon footprint of the products that they use, there is increased demand to develop mechanisms allowing them to access detailed product information. To that end, the EU Batteries Regulation will require that manufacturers disclose the carbon footprint of the batteries they place in the markets, allowing consumers to make more informed decisions when purchasing an EV. A standardized methodology for calculating this metric was initially expected by 2025 but has since been delayed (Regulation [EU] 2023/1542). Similarly, the Global Battery Alliance's Battery Passport will disclose battery information including the origins of its materials and its ESG score (Global Battery Alliance, n.d.).[13] The transparency of information about the social and environmental impacts of supply chains enables consumers and governments to reward supply chain actors who adopt better practices.

## Enabling circular battery supply chains

Given the pace of EV market growth and the long period of time before an EV battery reaches end of life, the potential for recycling to reduce new mineral demand for EV batteries may be limited in the short term but is a promising long-term solution. Previous ICCT research found that recycling could reduce the combined global annual demand for raw cobalt, lithium, manganese, and nickel by 1% in 2030 and by 16%–18% in 2050 (Li et al., 2024). However, achieving this potential reduction in materials and the associated climate benefits will require policies that enable batteries to be efficiently collected and recycled (Tankou et al., 2023). The following subsections detail key policy measures to support circular battery supply chains, including measures to ensure that battery data are easily accessible and that batteries are properly traced, collected, and recycled.

13 An ESG score rates how well battery manufacturers fare with respect to social and environment factors like the prevalence of child labor and the amount of water consumed in mining operations (Global Battery Alliance, n.d.).

### Battery traceability

To ensure that end-of-life EV batteries are collected for recycling, robust traceability mechanisms are essential. Some governments have already introduced requirements for traceability mechanisms. For example, the Chinese government launched the Battery Traceability Management Platform, which assigns each battery a unique code for lifetime tracking (China Ministry of Industry and Information Technology, 2024a). A similar initiative is being deployed at the global scale through the Global Battery Alliance's Battery Passport, which will allow the tracing and tracking of batteries worldwide throughout their lifetime (Global Battery Alliance, n.d.).

### Extended producer responsibility rules

Extended producer responsibility (EPR) mandates that manufacturers bear responsibility for collecting end-of-life batteries (China Ministry of Industry and Information Technology, 2018; General Office of the State Council, 2016; Regulation [EU] 2023/1542). While the EU and China have already implemented EPR laws, EPR laws are less developed in the United States. However, in 2024, New Jersey became the first U.S. jurisdiction to enact an EPR law for EV batteries under the Electric and Hybrid Vehicle Battery Management Act (2025), offering a pathway that other states could follow. The law mandates proper collection and management of end-of-life EV batteries and bans landfill disposal by January 2027. Battery producers—individually or collectively—must develop a battery management plan detailing the processes for battery collection, transportation, remanufacturing, repurposing, and recycling, as well as procedures for stakeholder education and financing.

### Battery data sharing

EV batteries typically arrive to third party reuse and recycle centers as "black boxes," meaning that they lack critical information needed to allow safe and affordable repair, reuse, and recycling. In the United States, the Advanced Clean Cars II regulations adopted in California require that batteries introduced in the market from 2026 onward come with a label that provides critical information about the battery's chemistry (California Air Resources Board, 2022a). A digital identifier will also be displayed on the label to enable vehicle manufacturers and other approved entities to access information on safe EV battery repair and disposal operations (California Air Resources Board, 2022a). Similarly, battery passports in the EU will enable legitimate third parties to have access to key information for repairing, reusing, and recycling EV batteries, such as a protocol for dismantling the battery, detailed information about the composition of the cathode, and contact details for replacement parts (Regulation [EU] 2023/1542).

### Recycling requirements

The EU Batteries Regulation introduces element-specific recovery targets of 50% for lithium and 90% for copper, nickel, and cobalt. From 2031, these will increase to 80% for lithium and 95% for cobalt, copper, and nickel. In addition to the element-specific recovery rates, starting in 2025, 65% of all material (by weight) in a battery must be recovered, with this rate increasing to 70% from 2030. Finally, the regulation also states that newly manufactured batteries with a capacity larger than 2 kWh will be required to include a certain share of recycled material. From 2031, this means that at least 16% of the cobalt, 6% of the lithium, and 6% of the nickel used in the battery cell must be recycled material. From 2036, these proposed targets will increase to 26% for cobalt, 12% for lithium, and 15% for nickel.

In China, the government introduced new industry standards for the responsible management of end-of-life EV batteries in 2024. These standards went into effect on January 1, 2025, and existing industries have 1 year to comply. The standards set minimum capacity requirements of 1,000 tons per year for battery reuse plants and 5,000 tons per year for recycling plants. Furthermore, plants must integrate automated, energy-efficient, and environmentally friendly technologies, and they may not be built in protected ecological areas. Plant activities must also be traceable through the national battery traceability platform. The standards additionally lay out requirements for second-life batteries, including ensuring battery quality before re-entering the market and making batteries traceable to enable after-sale services and real-time monitoring for second-life applications. In terms of recycling battery materials, the standards also introduce several material recovery targets: at least 98% recovery for electrode powder, 90% recovery for lithium, 98% for nickel, cobalt, and manganese, and 90% wastewater recycling (China Ministry of Industry and Information Technology, 2024b).

## Embedding sustainable battery criteria within EV supply- and demand-side policies

Although not the primary purpose of these regulations, supply-side regulations (SSRs) offer an opportunity to encourage more sustainable batteries. SSRs—which refer to policies targeting product manufacturers rather than consumers—are commonly used across the globe to regulate vehicle markets. In particular, they are a powerful tool to ensure that manufacturers develop and sell increasing numbers of clean vehicles in order to meet binding targets. These typically take the form of performance-based standards that regulate average fuel consumption and $CO_2$ emissions or ZEV sales requirements that set annual targets for the share of ZEVs to be sold by each manufacturer. These policies, in some form, have been adopted in markets covering 63% of the global light-duty vehicle market as well as in the largest heavy-duty markets like those of China, the EU, India, and the United States (Hall, 2024).

There are two general policy approaches to encourage improved battery sustainability, depending on whether the sustainability criteria in question are mature or more novel. For very well-established pathways or baseline characteristics that can be met by all vehicles, standards can set minimum requirements with mandatory compliance. These could include battery durability and labeling requirements, minimum recycled content standards, and compliance with baseline transparency and due diligence schemes. This approach is demonstrated in policies like California's Advanced Clean Cars II regulations and the United Kingdom's ZEV sales requirements, which include stipulations on characteristics like battery durability (Department for Transport, 2024). These criteria can also be enforced in emissions standards. Notably, the Euro 7 standard, which goes into effect in 2026, includes similar requirements for battery durability as the SSRs in California and the United Kingdom (Regulation [EU] 2024/1257).

In other cases, certain certifications or technologies to improve battery sustainability may be promising but ultimately too costly or insufficiently available under current market conditions to make their inclusion mandatory; examples include requiring high shares of recycled materials, certifying use of 100% renewable energy in manufacturing, or obtaining voluntary best-practice certifications for responsible mining. In these cases, providing incentives within SSRs—such as bonus credits for ZEV sales requirements and off-cycle credits for performance-based standards—is an effective way to encourage further development of early-stage technologies. Importantly, the value of these credits must be limited so as not to dilute the overall stringency of the standards.

Alternatively, demand-side policies can also encourage battery sustainability criteria, such as EV incentive designs that make these criteria a condition for receiving the incentive as a whole or in part. For instance, the "ecological bonus" incentive in France requires vehicles to achieve a certain environmental score reflecting the vehicle's production emissions. The environmental score assigns default emissions-intensity values based on the battery's chemistry and the region in which it was produced but not the energy source or processes used at a specific factory. Given this methodology, the incentive has the effect of excluding several models imported from regions that have more carbon-intensive energy supply and including those produced in Europe (Negri & Bieker, 2025b). Nevertheless, this design choice also means that there is no incentive for companies to improve the emissions intensity of their own operations. Schemes could therefore more effectively support lower-carbon batteries by factoring in the energy and materials used to produce those specific batteries.

Table 4 summarizes several examples of how SSRs and purchase incentives encourage or require battery criteria. Some of these examples (e.g., the Inflation Reduction Act) do not explicitly promote a lower carbon footprint but nonetheless demonstrate how such a policy could be constructed.

**Table 4**. Battery sustainability requirements in major supply- and demand-side policies

| Jurisdiction | Policy | Battery criterion | Description | Source |
|---|---|---|---|---|
| **Supply-side regulations** | | | | |
| **California** | Advanced Clean Cars II | Battery warranty, labeling for recycling | Minimum 70% battery state of health for 8 years or 100,000 miles for model years (MYs) 2026–2030 or 75% for MYs 2031+ | California Air Resources Board (2022a); California Air Resources Board (2022b) |
| **European Union** | Euro 7 | Battery durability | Minimum 80% capacity after 5 years or 100,000 km, minimum 72% after 8 years or 160,000 km | Regulation (EU) 2024/1257 |
| **United Kingdom** | Vehicle Emissions Trading Scheme | Battery warranty | Minimum 70% battery state of health for 8 years or 100,000 miles | Department for Transport (2024) |
| **Purchase incentives** | | | | |
| **France** | Eco-bonus | Minimum environmental score of 60 out of 80 | Score based on location of production, vehicle material composition, recycled content, and vehicle efficiency | Agence de l'Environnement et de la Maîtrise de l'Énergie (n.d.) |
| **Luxembourg** | Clever Fueren | Maximum criteria on battery electricity consumption | €8,000 for an electric passenger car purchased or leased with electricity consumption of less than 180 Wh/km | Government of Luxembourg (2025) |
| **United States** | Inflation Reduction Act tax credit | Battery mineral origin | Minimum percentage of battery minerals (based on value) must come from the United States or countries with free trade agreement | U.S. Department of the Treasury (2023) |

While this policy approach shows promise, Table 4 illustrates that there is limited international alignment around independent certification schemes or simple metrics to indicate environmentally friendly batteries. As these schemes gain credibility, integrating them into SSRs and incentive programs could help to standardize good practices across the industry, increasing their benefits and lowering the cost of compliance.

# Conclusions

This report examined the current state of battery mineral supply chains, assessed industry and intergovernmental efforts to improve practices, explored technological pathways for reducing environmental impacts, and reviewed policy mechanisms to accelerate change. The following conclusions synthesize the report's findings and highlight the most promising opportunities for governments to ensure that the EV transition proceeds in an environmentally and socially responsible manner.

**Mineral processing and manufacturing are the primary drivers of batteries' GHG footprint, but mining is associated with other substantial environmental harms.** Refining and processing of key battery minerals like lithium, nickel, and cobalt are typically very energy intensive and account for 5 to 50 times more emissions than the mining of those same minerals. For nickel-rich NMC batteries, the mining, processing, and refining of key battery materials (e.g., LiOH, $NiSO_4$, $CoSO_4$, and graphite, with $NiSO_4$ and graphite accounting for the most emissions) together account for up to half of the battery's GHG footprint, with the remainder coming from manufacturing of anodes, cathodes, cells, and packs. While mining itself is not a large contributor to the GHG emissions of batteries, it can cause significant local pollution and resource depletion that affect local communities and ecosystems. Minimizing these impacts—including water depletion, biodiversity loss, toxic waste generation, and labor rights violations—requires both adoption of demonstrated best practices and stronger regulatory frameworks.

**Switching to lower-carbon energy in battery manufacturing and leveraging chemistry innovations are the greatest opportunities to reduce the embedded GHG emissions of batteries.** Modeling based on the GREET emission factors database found that LFP batteries made with solid-state synthesis preparation had roughly 25%–30% lower embedded GHG emissions per kWh than NMC batteries, although other research has found that the embedded carbon of LFP or NMC could be higher depending on processes and materials. Regardless of chemistry, using more renewable energy and switching from direct combustion of fossil fuels to electricity whenever possible can reduce emissions for all chemistries. For that reason, production in a region with low-carbon electricity like Norway can result in embedded emissions approximately 35% lower than in a region with high-carbon electricity. Furthermore, although research is mixed on the carbon intensity of emerging battery technologies (e.g., solid-state and sodium-ion batteries), continuous innovation and greater economies of scale for all battery chemistries could deliver climate benefits.

**Improved battery durability and recycling can meaningfully reduce the climate impacts associated with batteries over the long term.** Beyond increasing the use of renewable electricity in battery manufacturing, reducing the number of new batteries produced by ensuring that batteries last longer is another way to decrease the cumulative GHG emissions of batteries and minimize other environmental and social harms associated with the EV transition. Through regulations, governments can help to ensure that batteries can last at least the lifetime of a car and can eventually be recycled. Supply-side regulations can also mandate expanded producer responsibility programs as well as technical requirements to limit GHG emissions associated with battery production (e.g., battery durability). Moreover, studies have shown that hydrometallurgical recycling results in greater carbon savings (up to 17%) than pyrometallurgical recycling (up to 9%), and policymakers could consider this when designing and implementing policies and regulations regarding battery recycling. Finally, novel technologies like direct recycling could provide yet greater climate benefits in the long term.

**Numerous guidelines, certification schemes, and standards have been developed to promote low-carbon, responsible mining and battery manufacturing, but more consistent policy backing is needed to enable mainstream adoption.** Many expert organizations have thoughtfully evaluated battery sustainability, resulting in robust certification schemes and due diligence requirements like the Global Battery Alliance's Battery Passport and the Responsible Minerals Initiative. Although such schemes will require updates as the industry advances, their existence means that governments need not invent new requirements from scratch. Instead, more consistent and widespread support of these existing frameworks in leading markets can encourage the global EV industry to harmonize around a common set of standards, achieving greater benefits while reducing the cost of compliance. This could be accomplished by integrating these requirements into incentive schemes, type approval, or SSRs. In addition to minimum standards for supply chain responsibility, incentives for EV and battery manufacturers to improve the social and environmental responsibility of their supply chains can reward upstream mining companies who adopt better practices.

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