38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Technologies and policy levers for more sustainable batteries

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Executive summary

Consumers are becoming increasingly sensitive to the origin of the raw materials used in their products and whether ethical and sustainable practices were embedded throughout their production [1][2]. Facing increased pressure from consumers, regulators, and advocacy groups for more responsible sourcing, the mining industry is progressively incorporating Environmental, Social, and Governance (ESG) standards within their activities. This report highlights how the transition to cleaner electricity, advancements in battery technology, and the implementation of policies that promote transparency, traceability, data sharing, and recycling can contribute to more sustainable and socially responsible battery supply chains.

Keywords: electric vehicles, battery manufacturing, mining, material for EVs, life cycle analysis

1 Technologies and techniques for sustainable batteries

1.1 Best practices for more sustainable mining and processing

1.1.1 Carbon footprint of the mining and processing of key electric vehicle battery minerals

Before a battery can be produced, the constituent minerals must be extracted, refined, and transported to locations for further production. The processes for extraction and refining, and the associated emissions, vary significantly according to the mineral and the specific mine in question, and understanding the relative contribution of the different inputs to a battery's carbon footprint is essential for reducing emissions. As a starting point, the Research & Development Greenhouse gases, Regulated Emissions, and Energy use in Technologies 2024 (R&D GREET) model developed by Argonne National Laboratory was used to conduct a baseline inventory of the carbon intensity of selected minerals used in electric vehicle (EV) batteries [3]. Figure 1 below shows the CO_2 emissions associated with producing a kilogram of nickel, cobalt, lithium, and natural graphite; where possible, this is broken down by stage (mining and extraction, processing and refining, and transportation logistics).

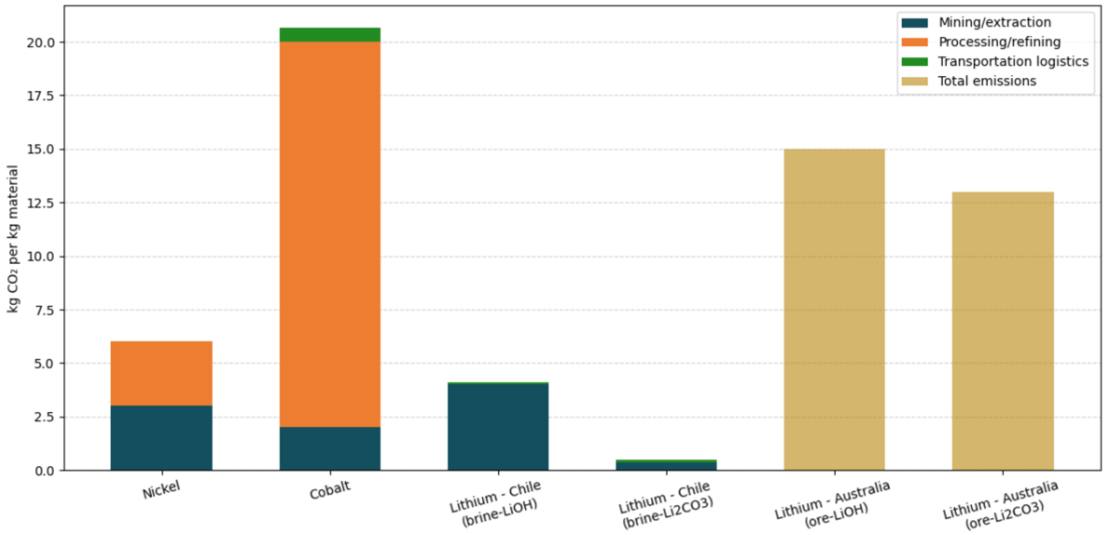

Figure 1: Embedded CO_2 emissions for the mining and processing/refining of selected key materials used in electric vehicle batteries

As shown in Figure 1, cobalt exhibits the highest CO_2 emissions intensity per kilogram of material, driven almost entirely by energy-intensive processing and refining steps. Lithium hydroxide (LiOH) and lithium carbonate (Li_2CO_3) derived from hard-rock ore in Australia also show high emissions. In contrast, lithium sourced from brine—particularly brine-based Li_2CO_3—has substantially lower emissions due to its reliance on solar evaporation rather than fossil-fuel-intensive processing. Nickel ranks in the mid-range for emissions per kg. Not shown in Figure 1 are emissions from graphite, an element used for anode production. According to Benchmark Mineral Intelligence, synthetic graphite can be up to four times more carbon intensive than natural graphite [4]. Finally, except for lithium carbonate from brine in Chile, transportation and logistics make up a minor share of total emissions compared to mining and processing stages (up to 3%).

1.1.2 Typical mining and processing techniques for battery minerals

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. For lithium, for example, methods seen in countries like China and Australia consist of hard rock mining, in which rocks rich in lithium (i.e., spodumene) are mined, crushed, and treated at high temperatures on the order of 1,000 °C (1,832 °F). After cooling, the material is pulverized and chemically treated to extract the lithium, which is then refined into lithium carbonate or lithium hydroxide which can be used in EV lithium-ion battery production [5][6].

In countries like Argentina, Bolivia, and Chile—collectively known as the "Lithium Triangle"—lithium is extracted from brine, a salty solution containing dissolved lithium found underground. The first step consists of pumping the brine to the surface into evaporation ponds where it sits for months or years until enough water evaporates (through sunlight and wind) to reach the desired concentration of lithium. From there, the lithium solution is pumped to a recovery facility for processing. Typical processing steps include pretreatment to remove contaminants, chemical treatment to isolate the lithium, filtration to separate the lithium from other products, and treatment with reagent to obtain lithium carbonate or lithium hydroxide as a final product. Once the lithium extraction is complete, the remaining brine is typically returned underground [6][7][8].

Cobalt is often mined as a by-product of copper and nickel mining. The minerals are extracted from the surface (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 ore. The next step is crushing and grinding the ore to prepare it for hydrometallurgical processing, where it undergoes acid leaching under high temperatures (i.e., 695–705 °C) and pressure to separate the cobalt from other unwanted materials in the ore. Finally, the cobalt is precipitated and refined to achieve a high purity product suitable for EV battery manufacturing [9][10].

1.1.3 Sourcing of energy for mineral mining and processing

For the operations described above, large amounts of electricity are typically used to power mechanical processes including drilling, grinding, and crushing, as well as supporting systems such as ventilation in underground mining, dewatering pumps, conveyors belts for ore transport or chemical refining processes such as electrowinning for cobalt. Meanwhile, thermal energy derived from fossil fuels such as diesel is typically used to power up transportation logistics within the mine. Additionally, fossil fuels like coal, natural gas, or fuel oil are used to supply high temperatures needed for pyrometallurgical processes (e.g., smelting and roasting) [11][12]. Considering that energy is one of the biggest expenses of mining companies, representing up to 30% of their operating costs, the decreasing price of renewable energies presents an opportunity to significantly reduce costs alongside emissions [13]. Renewable electricity sources supported by battery energy storage can be used to convert mining and refining to run on clean energy. Processes using thermal energy that cannot easily be electrified, such as heating from natural-gas boilers, can be powered by green electrolyzed hydrogen produced with renewable electricity.

There is evidence that the transition towards clean energy in the mining sector is feasible and cost effective. 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 [11]. In Chile, the mining company BHP has signed 15-year power agreements to supply its coal-based Escondida and Spence copper mines with 100% renewable electricity produced from wind and solar. BHP estimated that this will reduce 3 million tons of CO_2 per year compared with 2020 levels, while reducing operational costs by 20% [14]. In 2022 and 2023, the company achieved 100% renewable electricity use it its two Chilean mines [15].

To address the intermittency of solar and wind energies, or to accommodate mines that are in off-grid areas, battery energy storage systems have proven effective in ensuring continuous operations. In Australia, for example, the copper and gold mining company, Sandfire, integrated a 6-MW solar powered energy storage system to its 19 MW diesel fired power station. This has enabled 20% of annual power to be provided by solar energy and a reduction of CO_2 emissions of 12,000 tons annually [16].

1.1.4 Zero-emission mining and machinery

Mining equipment and vehicles such as trucks, loader tractors, haulage cranes, and excavators present another area where the adoption of cleaner technologies can help decarbonize the sector. Traditionally, those vehicles and equipment have been powered by diesel and have contributed to greenhouse gas (GHG) emissions while also generating particulate matter, noise, and heat which compromises the health of mine workers [17][18]. The shift towards zero-emission vehicles and 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 productivity comparable with their diesel counterparts [19][20].

The use of electrified vehicles and machinery in underground mining is gaining momentum, with at least 53 mines having adopted or trialed battery electric vehicles as of 2024, mostly in North America. Electrification via overhead wires (i.e., a trolley system) is already a mature technology for mining trucks and is typically in a hybrid configuration with a diesel engine to reduce air pollution and fuel costs while providing greater power for heavy loads on steep routes [18]. Lessons learned from the use of electrified vehicles and machinery in those mines will therefore help to identify best practices and develop the knowledge to address the challenges and concerns currently confronted by the mining industry. These challenges include the need to train workers on operating or maintaining electrified equipment, minimizing of fire risks from battery electric vehicles operating underground, identifying best charging strategies to maximize productivity (e.g., direct current fast charging versus battery swapping), and optimizing design of mines to facilitate operational logistics [18].

2 Design and manufacturing approaches to reduce battery carbon footprint

2.1 Design and manufacturing approaches to reduce battery carbon footprint

Since its commercialization in the early 1990s, the lithium-ion battery has driven numerous innovations, including advances in cathode and anode chemistries that have improved both energy density and durability. The following subsections outline how these technological developments influence the carbon footprint of EV batteries.

2.1.1 Life cycle assessment of commercialized and prospective batteries

The International Council on Clean Transportation (ICCT) conducted a life cycle assessment that compares cradle-to-grave GHG emissions of four battery technologies (LFP produced via hydrothermal synthesis, LFP produced via solid state synthesis, NMC622, and NMC811) in China, Norway, and the United States using the R&D GREET model [3]. Data on grid electricity mix for the three countries were obtained from the International Energy Agency [20]. The analysis focuses on battery electric passenger cars with an 84-kWh battery. R&D GREET also assumes the lifetime of a battery electric vehicle to be 173,151 miles during which no battery replacement occurs. The results are presented under Figure 2 below [3].

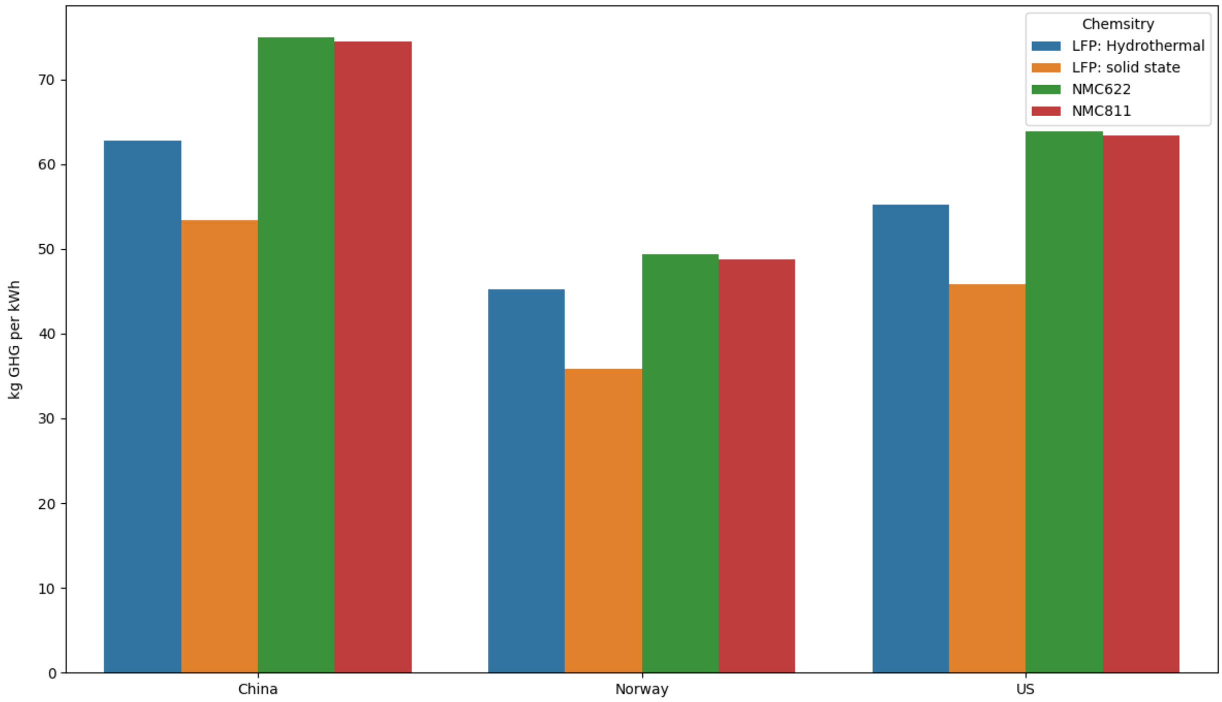

Figure 2: Life cycle analysis of LFP and NMC batteries in China, Norway and the United States

Figure 2 illustrates how chemistry, processing pathways and region of production influence the carbon intensity of EV batteries. China consistently shows higher carbon intensity across all chemistries, reflecting its carbon-intensive energy mix (60% coal), whereas Norway exhibits the lowest emissions for all chemistries, with its very-low-carbon electricity (i.e., 90% hydropower based). The United States falls in between, with a more varied electricity grid mix compared to the other two countries. LFP chemistries generally have comparable or lower carbon intensities than NMC (nickel manganese cobalt) within the same region. Among the LFP material processing routes, the solid-state pathway delivers more favorable environmental outcomes in terms of GHG emissions. The results also show that the NMC622 and the NMC811 chemistries show similar GHG emission footprints. Across the three countries studied, NMC622 and NMC811 tend to be more carbon-intensive than LFP, reflecting higher energy use for material processing, particularly for nickel and cobalt. At the same time, we note that the local electricity mix has a large influence on the carbon footprint of the battery: the most carbon-intensive chemistry produced with low-carbon electricity (in Norway) has lower emissions than the least carbon-intensive chemistry produced with high-carbon electricity (in China).

2.1.2 Impact of recycling on battery carbon footprint

This study also evaluates the impact of using recycled rather than virgin minerals on batteries' embedded GHG emissions, again using the R&D GREET model. We considered two recycling pathways, pyrometallurgical and hydrometallurgical recycling, for both NMC chemistry options. This analysis assumes that the recycled share of content matches the material recovery targets set by the European Union Battery Regulation (90% for cobalt and nickel and 50% for lithium), representing a situation in which recycling has been widely scaled. All other assumptions are consistent with those for Norway in Figure 2. The results are presented in Figure 3a (pyrometallurgical) and 3b (hydrometallurgical).

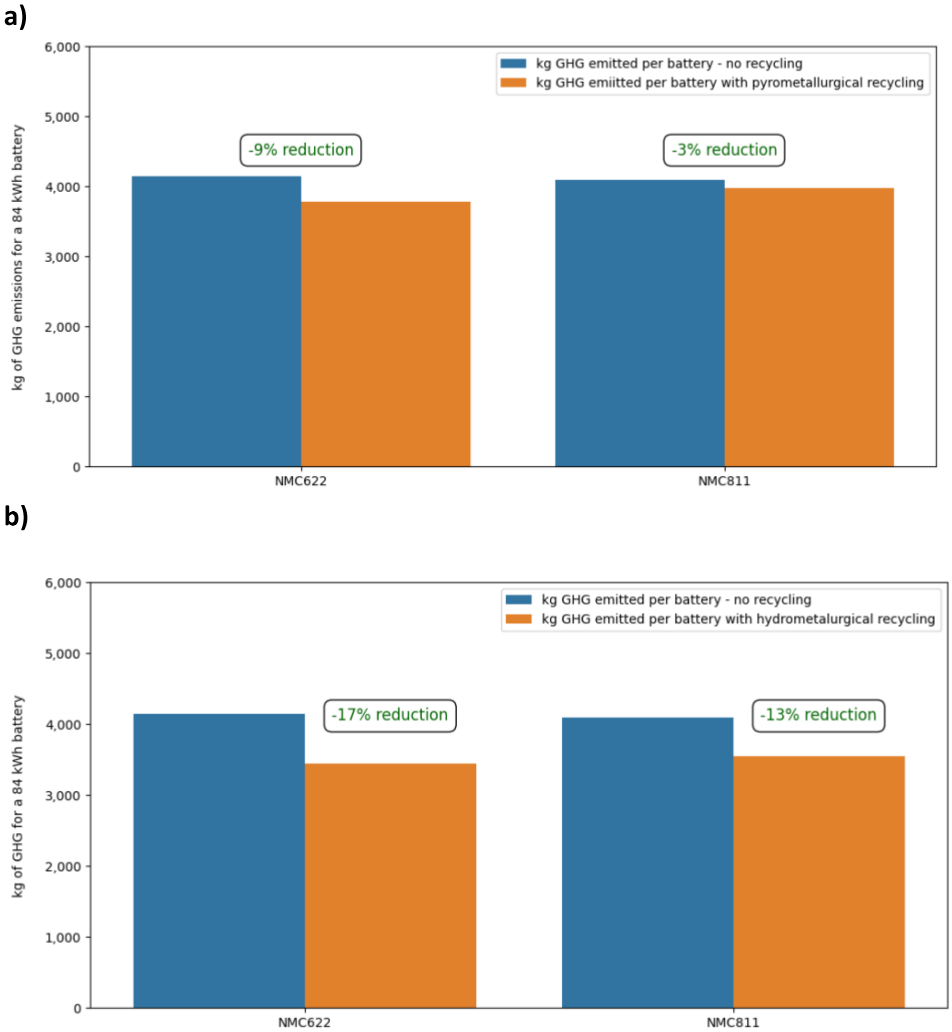

Figure 3: Impact of pyrometallurgical (a) and hydrometallurgical (b) recycled material on the carbon footprint of NMC622 and NMC811 batteries manufactured in Norway

Figure 3a illustrates how using recovered minerals in the manufacturing of NMC622 and NMC811 results in meaningful estimated reductions in total GHG emissions—about 9% and 3% respectively—when pyrometallurgical recycling is applied, reflecting the high recoverability of nickel and cobalt which displace the need for more energy-intensive virgin production. In comparison, Figure 3b shows that using hydrometallurgical recycled material in battery manufacturing can further reduce the carbon footprint of NMC622 and NMC811 batteries by an estimated 17% and 13% respectively. The hydrometallurgical approach typically delivers better environmental outcomes due to its less energy intensive processes and higher material efficiency recovery. Hence, while the use of recycled material is almost always beneficial for the carbon footprint of batteries, recycling pathways matter. Though not examined here, the potential emissions reductions for LFP batteries may be lower because there is no cobalt or nickel to recover and lithium cannot typically be recovered from purely pyrometallurgical processes.

2.1.3 Improvement in battery durability and density

Improvements in battery durability can extend the lifespan of EV batteries, therefore reducing pressure on the demand for new mining. Additionally, durable batteries enable second-life applications, such as energy storage systems, potentially further delaying the demand for newly mined resources. Several factors influence battery durability. One of these factors, is the chemistry: LFP batteries typically last longer than NMC batteries despite having lower energy density [22]. Another factor is the design of the battery, such as using cell-to-pack configurations whereby cells are directly assembled into packs without using modules. Cell-to-pack design allows better heat dissipation, as there are fewer structures trapping thermal energy, which means that the battery experiences less thermal stress and can last longer. In addition, cell-to-pack battery designs have a simpler structure with fewer opportunities for technical failures [23].

Innovations for higher density batteries (i.e. amount of energy stored by volume) offer another approach to reducing the need for newly mined minerals. By increasing energy density, batteries can de designed with smaller capacities, potentially requiring less material. Here again, the cell-to-pack structure proves advantageous as it also improves battery density by eliminating inert materials. A recent trend in the lithium-ion battery market is the shift towards higher nickel and lower cobalt content in NMC batteries. The substitution of cobalt with nickel results in higher energy densities. This suggests the demand for newly mined nickel could increase in the years to come, despite a potential decrease in cobalt demand. Another trend is incorporating silicon in graphite anodes or using fully silicon-based anodes to enhance energy density [24][25].

3 Policies and regulations to encourage more sustainable and socially responsible batteries

3.1 Frameworks for more socially responsible batteries

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. Examples of those schemes include the OECD Guiding Principles on Humans and Business Rights or the United Nations Guiding Principles on Business and Human Rights [26][27]. These schemes propose or enforce processes for governments and private companies to assess adverse impacts of their operations and activities on communities’ rights as diverse as access to water, adequate living standards, freedom of speech, and access to education. Diligence schemes also call for states and enterprises to establish grievance mechanisms to enable workers and populations affected by their activities to formulate complains an obtain remediation measures when their rights have been violated [26][27].

Because they are not industry specific, the implications of these frameworks for specific sectors like EV battery manufacturing must be adjudicated. In recognition of this, The European Union, through its Battery Regulation, will require that by August 2025, all economic operators that produce or sell EV batteries to the European Union market develop due diligence policies. These will have to align with internationally recognized due diligence provisions and detail measures that the economic operators will undertake to minimize social and environmental risks associated with their activities. These social and environmental risk categories are detailed under Annex X of the EU Battery Regulation and include soil pollution, energy use, biodiversity, and child or forced labor [28].

Another international framework of note is the principle of Free, Prior, and Informed Consent (FPIC) which sets out rights of indigenous and tribal peoples over their natural resources and habitats and the responsibility for governments to protect those rights. FPIC recognizes the right of indigenous and tribal people to give or refuse consent for any activities like mining that would affect their lands. 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. While some jurisdictions such as Bolivia and the province of British Columbia, Canada have incorporated UNDRIP into their legal frameworks, FPIC is not a legally binding requirement in most countries [29]. From an energy security perspective, however, not seeking consent from local or indigenous people could lead to tensions and conflicts which delay mining projects, negatively impacting consumer and investor confidence in mining companies. Adhering to the FPIC could therefore lead to more sustainable mining while mitigating risks in mineral supply chains.

Promoting battery ESG transparency

As consumers become more sensitive to the social and carbon footprint of the products that they use, mechanisms have been developed that would allow them to access such information. Effectively, In 2025, the EU Battery regulation will require that manufacturers declare the carbon footprint of the batteries they place in the markets. A standardized methodology for the calculation of this metric is also expected by 2025 [28]. This will allow consumers to make more informed decisions on sustainability when purchasing an EV. Similarly, the Global Battery Alliance passport will disclose battery information including the origins of its materials and its ESG score determined by social and environment factors like child labor and water consumption [30]. In Germany, a revamped labeling program, the German Car Energy Consumption Labelling Ordinance for passenger cars, was introduced in February 2024, requiring manufactures to disclose information on the vehicle's fuel or energy consumption and CO_2 emissions, among other metrics, when advertising new vehicles at a dealership or online [30].

3.2 Towards more transparent and sustainable electric vehicle battery supply chains: traceability, data sharing, and end of life management

Given the pace of growth of the EV market, the potential for recycling to reduce new mineral demand for EV batteries is limited in the short term but is a promising long-term solution. Previous ICCT research further estimated that recycling could reduce the combined annual demand for raw cobalt, lithium, manganese, and nickel by 3% in 2030, 11% in 2040, and 28% in 2050 [31]. Achieving this potential reduction in material demand and the related climate benefits identified above, however, will require policies that mandate batteries be efficiently collected and recycled.

Battery traceability

To ensure that end-of-life EV batteries are collected, robust traceability mechanisms are essential. In China, the government launched the Battery Traceability Management Platform in 2018, assigning each battery a unique code for tracking over its lifetime. In the European Union, the EU Battery Regulation will introduce a battery passport—a digital representation of the physical battery—that enables tracing and tracking of the batteries [28]. A similar initiative is being deployed at the global scale through the Global Battery Alliance battery passport which will allow the tracing and tracking of batteries worldwide throughout their lifetime [32].

Extended producer responsibility rules

In 2024, New Jersey became the first U.S. jurisdiction to enact an Extended Producer Responsibility law for EV batteries under the Electric and Hybrid Vehicle Battery Management Act [33]. The law mandates proper collection and management of end-of-life EV batteries and bans landfill disposal by January 2028. Producers of EVs—individually or collectively—are required to develop a battery management plan detailing collection, transportation, remanufacturing, repurposing, and recycling processes, stakeholder education, and financing. Extended Producer Responsibility laws also exist in the European Union and in China, assigning the responsibility to manufacturers to collect end of life batteries [28][34][35].

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 of the batteries. In the

United States, the Advanced Clean Cars II regulations developed by California will require that by 2026, batteries introduced in the market come with a label that provides information on its chemistry, which is necessary to optimize recycling.

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 [36]. Similarly, in the European Union, the battery passport will enable legitimate third parties to have access to key information such as dismantling protocol, composition of the cathode, and contact details for replacement parts to enable repair, reuse, or recycling [28].

Recycling requirements

Starting in 2027, the EU Battery 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 copper, nickel, and cobalt. In addition to the element-specific recovery rates, 65% of all material (by weight) in a battery must be recovered from 2025, increasing to 70% from 2030. Finally, the EU Battery regulation will also require that newly manufactured batteries with a capacity larger than 2 kWh include a certain share of recycled material. From 2031, this would require at least 16% of the cobalt, 6% of the lithium, and 6% of the nickel used in the battery cell are recycled material. From 2036, these proposed targets increase to 26% for cobalt, 12% for lithium, and 15% for nickel [28].

In China, the government introduced in 2024 new industry standards for the responsible management of end-of-life electric vehicle batteries. They became effective as of January 1, 2025, and existing industries have 1 year to comply. The standards also set a minimum capacity requirements of 1,000 tons per year for battery reuse plants and 5,000 tons per year for recycling plants. Furthermore, plants may not be built in protected ecological areas; must integrate automated, energy efficient, and environmentally friendly technologies; and their activities must be traceable through the national battery traceability platform. Requirements have also been established for second life batteries, including quality assurance before re-entering the market and traceability requirements to enable after sale services and real time monitoring as they are deployed in second life applications. On the recycling side, several material recovery targets have been introduced: at least 98% recovery of electrode powder, 90% recovery of lithium, 98% of nickel, cobalt, and manganese, and 90% of wastewater [37].

Moreover, the standards require reuse and recycling plants to be in alignment with China's work safety and health law, which translate into measures such as assessing workplace hazards, staff training, or establishing digital tracking systems for battery waste [36].

3.3 Embedding sustainable battery criteria within electric vehicle supply- and demand- side policies

Supply-side regulations are a powerful tool to ensure that manufacturers develop and sell increasing numbers of clean vehicles to meet binding targets. These typically take the form of performance-based standards which regulate average fuel consumption or CO_2 emissions, or zero-emission sales requirements that set annual targets for the share of zero-emission vehicles 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 the largest heavy-duty vehicle markets of China, the European Union, India, and the United States [38].

While not the primary purpose of these regulations, these also offer an additional opportunity to encourage more sustainable batteries. For very well-established production pathways or baseline characteristics that can be expected of all vehicles, standards can set minimum requirements. This approach is already demonstrated in California's Advanced Clean Cars II regulation and in the United Kingdom, where ZEV sales requirements include stipulations on characteristics like battery durability.

Battery sustainability criteria can also be encouraged through EV incentives by making these criteria a condition for receiving part or all of the incentive. In some cases, these may overlap with industrial or national security considerations. The "ecological bonus" incentive in France requires models to achieve a

certain environmental score accounting for the carbon footprint of the vehicle; this has the effect of excluding several imported models, but not those produced in France.

Table 1 summarizes several examples of how battery criteria are encouraged or required through supply-side regulations and purchase incentives

Table 1: Summary of battery sustainability requirements in major supply- and demand-side policies

Jurisdiction	Policy	Battery criterion	Description
		Supply-side regulations	
California [39]	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 2026–2030 or 75% for model years 2031+
European Union [40]	Euro 7	Battery durability	Minimum 80% capacity after 5 years or 100,000 km, minimum 72% after 8 years or 160,000 km
United Kingdom [41]	Vehicle Emissions Trading Scheme	Battery warranty	Minimum 70% battery state of health for 8 years or 100,000 miles
		Purchase incentives	
France [42]	Eco-bonus	Minimum environmental score of 60 out of 80	Score based on the carbon footprint of the electric vehicle
Luxembourg [43]	Clever Fueren	Maximum criteria on battery electricity consumption	€8,000 for a passenger electric car purchased or leased with electricity consumption of less than 180 Wh/km
United States [44]	Inflation Reduction Act tax credit	Use of recycled material	Federal incentive program that encourages the use of recycled material produced in North America in the manufacturing of new batteries

4 Conclusions

This report offers the following conclusions about the factors influencing the environmental impact of electric vehicle batteries and opportunities for governments to reduce those impacts.

Manufacturing contributes the largest share of GHG emissions associated with EV batteries, but the mining and processing of battery materials is associated with substantial environmental and social harms. Refining and processing of raw minerals is typically very energy intensive and accounts for more emissions than the mining of key battery materials, particularly lithium, cobalt, and graphite. In a typical NMC battery, nickel and graphite would contribute the largest share of emissions. Manufacturing of the cells and packs contributes additional emissions, which generally account for the majority of batteries' carbon footprint, although this is highly dependent on the sources of energy used for manufacturing. Transport and logistics across the value chain represents only a small portion (roughly 3% or less) of total emissions. While mining is not a large contributor of GHG emissions in batteries, it can cause significant pollution affecting local communities and ecosystems, and more sustainable practices could be encouraged.

Switching to renewable electricity for battery manufacturing and using low carbon chemistries provide the greatest opportunities to reduce batteries' embedded GHG emissions. Both battery chemistry as well as the manufacturing process impact the carbon intensity of lithium-ion batteries. LFP batteries are estimated to have roughly 10%–20% lower embedded CO_2 emissions than NMC batteries per kWh, with the solid state synthesis offering an additional 10%–20% reduction. Using more renewable energy, and switching from thermal to electrical power whenever possible, can reduce emissions for all chemistries. For that reason, production in a region with low-carbon electricity like Norway can result in estimated embedded emissions 30%–40% lower than in a region with high-carbon electricity like China.

Improved battery durability, higher energy density, and recycling can substantially reduce the environmental damage associated with batteries over the long term. Beyond reducing emissions and other environmental and social harms per unit of battery produced, reducing the number of new battery materials needed is also a promising and feasible route to reducing cumulative GHG emissions and other environmental and social harms. Governments can help to ensure that batteries can last the lifetime of the vehicle and are eventually recycled through regulations, extended producer responsibility programs, and technical requirements within supply-side regulations. Hydrometallurgical recycling has been shown to result in greater carbon savings than pyrometallurgical recycling and should be promoted.

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