



WHITE PAPER

Powering the Future

Unlocking Battery Electric Vehicle Sustainability
Through Strategic Battery Sourcing

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Introduction

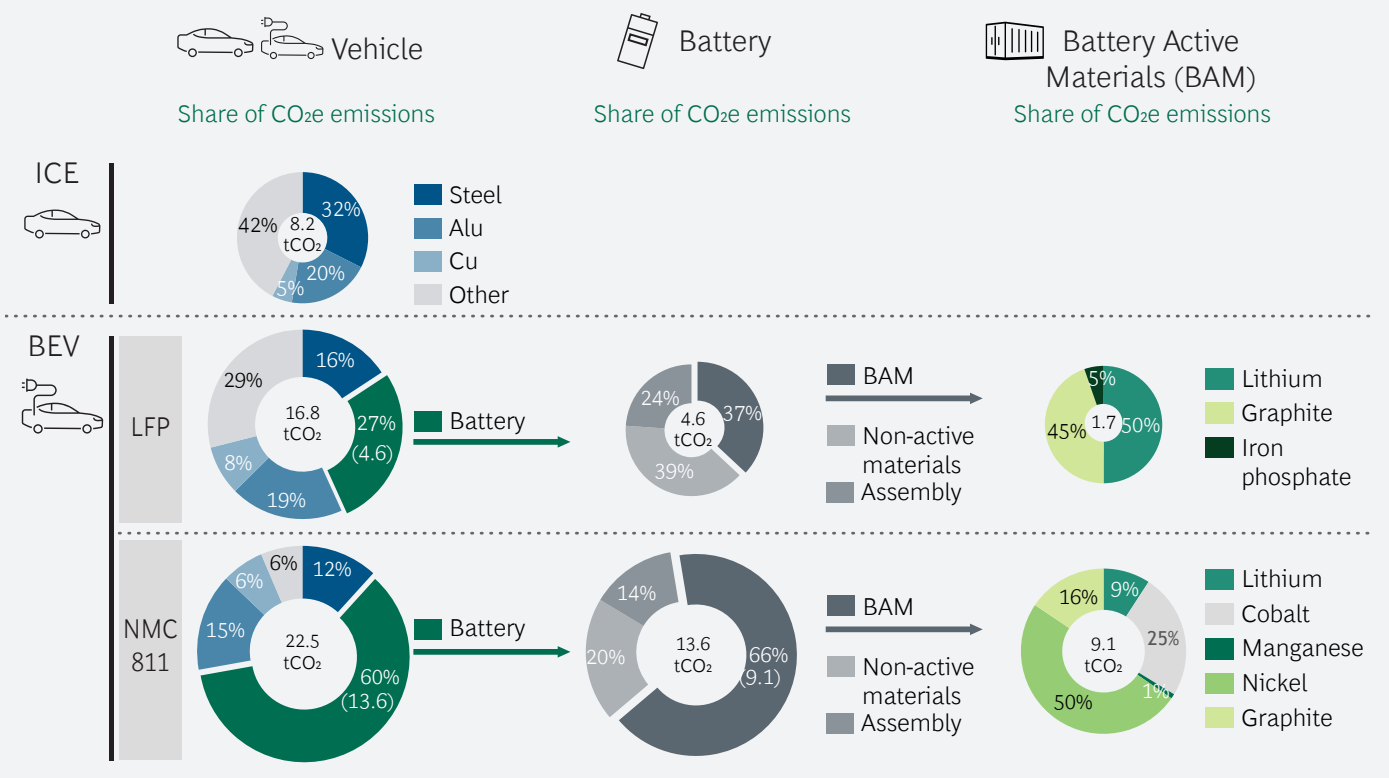
As nations strive to reduce emissions, transitioning from internal combustion engine (ICE) vehicles to electric vehicles (EVs) is essential.

EVs offer clear environmental benefits over ICE vehicles, due to their lower operating emissions, particularly when powered by renewable energy.

However, the emissions associated with EV battery production are an urgent concern, because while they do not undermine the overall sustainability of EVs, they clearly present an opportunity for further transparency and improvement. Only by understanding the sources of emissions in battery production as well as battery material production can decision-makers explore ways to reduce them.

Our focus is on traction batteries, which power the vehicle's electric motor and are one of the largest contributors to emissions in EV production. Emissions sourced from raw (battery) materials for them account for more than a third of the total CO₂ equivalent (CO₂e) of an average Battery Electric Vehicle (BEV). In addition, the CO₂e emissions of a BEV are nearly double those of an ICE vehicle due to the higher raw-material requirements, based on the average battery production in Asia, not taking green grid impact into consideration. Because the choices of raw battery materials—including their extraction and processing—occur early in the supply chain, before the product reaches the manufacturer, these decisions have a sizeable impact on scope 3 upstream emissions.

Exhibit 1 | Production emission depending on battery type



Note: Outside in view
Source: BCG analysis

Thus, at every stop along the supply chain—from materials miners and producers to metal and battery recyclers, battery manufacturers, and EV makers—companies must focus on understanding the emissions, the supply-demand profile and the relative cost profile of different sourcing options to understand the tradeoffs and set up their supply chains accordingly and leverage both green primary sourcing and recycling. Ensuring access to supply from low-emissions production routes, expanding recycling facilities, and securing secondary materials such as end-of-life (EOL) batteries are all critical to long-term sustainability and maintaining a competitive advantage. By balancing both recycling and sustainable primary sourcing to meet future demand while minimizing environmental impact, companies can significantly reduce their carbon footprint and contribute to a more sustainable future.

The following paragraphs briefly highlight this paper's key insights:

- **Battery types:** We focus on the two most common battery types, NMC811 and LFP, named for the 8:1:1 ratio of nickel, manganese and cobalt used in the cathode and the use of lithium, iron, and phosphate, respectively. NMC batteries typically allow for faster charging and greater range by storing more energy in a smaller space, but they are costlier and have higher manufacturing emissions than LFP batteries. The lower energy density of LFP batteries means they weigh more for the same distance, and therefore BEVs using LFP batteries have a lower range compared to those with NMCs.
- **Emissions drivers:** Battery active materials (BAM), such as nickel, manganese, cobalt, lithium and graphite, store and release energy in a battery—they are the key technology component of the battery. For NMC batteries, these materials are responsible for 60–70% of the total CO₂e production emissions per kWh, compared to 35% for LFP batteries. While decarbonizing BAM is crucial to reducing emissions without compromising battery performance, decarbonizing other materials, given their considerable share particularly in LFP batteries, must also be considered.
- **Decarbonization levers:** We consider two key levers to decarbonize BAM: primary (sourcing green primary materials) and secondary (recycling). Green battery production requires both, as the availability of green primary and secondary materials and capacity may be limited in the future.
- **Impact of sourcing lever ("primary lever"):** Green sourcing of BAM can significantly reduce emissions. For NMC batteries, the most emission-intensive sourcing methods (grey/black sourcing) produce about 180 kg CO₂e per kWh, versus ~70 kg CO₂e per kWh for green sourcing, a reduction of about 60%. For LFP batteries, using grey/black materials creates approximately 85 kg CO₂e per kWh, versus about 30% to ~60 kg CO₂e per kWh for green sourcing. For individual materials, emissions reductions of >90% are possible compared to grey/black sourcing. While BAM's primary emissions reduction potential is significant, the limited supply of green materials and intense competition for them make reducing gray material emissions by implementing ESG-compliant strategies essential—though this will be more achievable for certain gray sources than others, given the broad range of gray sourcing available.
- **Impact of recycling lever ("secondary lever"):** Recycling is the lowest CO₂e option for some BAM materials and plays a key role in emissions reduction, though not always matching the reduction possible with sustainable primary sourcing. While expected to contribute only 10%–20% of total BAM supply by 2030, the scarcity of green primary and secondary BAM makes recycling a necessity. In addition, it avoids mining-related concerns, helps meet recycling targets like those set by the European Union, and reduces supply-chain risks. Compared to grey/black sourcing, which results in ~180 kg CO₂ per kWh for NMC811 batteries and ~85 kg CO₂ per kWh for LFP batteries, recycling can reduce emissions by up to ~50% for NMC811 and up to ~25% for LFP. Newer recycling technologies currently in industrialization stage promise a further emission reduction potential.

CO₂e

To examine the carbon footprint of vehicles, we use CO₂ equivalent (CO₂e) as a standard unit to measure the impact of different greenhouse gases on global warming. Because greenhouse gases such as methane (CH₄) and nitrous oxide (N₂O) trap heat in the atmosphere to different degrees, CO₂e allows us to express their impact on global warming in a common unit (CO₂).

Battery types: how they differ and why we focus on LFP and NMC811

Lithium-ion batteries are the most widely used energy storage systems in electric vehicles, differing mainly in their chemical composition, which affects their performance, cost, and environmental impact.

For our study, we focus on Nickel Manganese Cobalt (NMC811)—named for the 8:1:1 ratio of nickel, manganese and cobalt used—and Lithium Iron Phosphate (LFP), which differ in cost, weight, and CO₂e emissions (see Exhibit 2, representing the average production in Asia).

NMC811 batteries are known for their high energy density, storing 265–290 Wh/kg at the cell level. At the battery level, including casing and cooling systems, they weigh between 6.2 kg and 7.2 kg per kWh. A 500 kg NMC811 battery can deliver 75 kWh, significantly more than a comparable LFP battery, which provides 55 kWh. This makes NMC811 ideal for high-performance EVs where space and weight are critical. However, NMC811 batteries are costlier at around \$100 per kWh, approx. double that of LFP batteries, and can have more than twice the environmental impact.

Lithium Iron Phosphate (LFP) batteries are known for their long cycle life and strong safety profile due to a lower risk of thermal runaway, which causes a battery to catch fire. However, their lower energy density (160–200 Wh/kg) requires them to be larger or heavier, at 8.6 to 9.6 kg per kWh, compared to NMC811 batteries. LFP batteries are more cost-effective, with prices dropping to \$50 per kWh in 2024, about half the cost of NMC811 batteries, because they do not rely on scarce materials like cobalt and have seen an increase in production scale. Additionally, LFP batteries, generating significantly lower CO₂ emissions, are a more environmentally friendly option. However, recycling remains challenging due to the absence of valuable materials for recovery beside lithium and low prices for new LFP batteries.

Exhibit 2 | Popular NMC811 and LFP batteries differ in cost, weight and CO₂ emissions

		NMC811 battery	LFP battery
Cost ¹ in \$ per kWh		~100	~50
Density ² in Wh per kg		265 – 290	160 – 200
Weight ³ in kg per kWh		6.2 – 7.2	8.6 – 9.6
Emissions ⁴ in kg CO ₂ e per kWh		~180	~85

¹Based on average battery cell prices in Asia ²Density at cell level ³Battery weight at pack level of 500kg, NMC battery 75 kWh, LFP battery 55 kWh; Cell level and pack level is not comparable, as pack level includes additional material such as casing, cooling system, etc.; Therefore, the numbers for weight and density cannot be matched ⁴Considering raw material sourcing from the most carbon intensive alternatives; Source: Conference of Metallurgists (COM) 2024

Source: BCG analysis

Further battery types (out of scope of this paper)

In addition to the most common LFP and NMC batteries, there are other types of lithium-ion batteries that are not the focus in this paper:

Nickel Cobalt Aluminum (NCA) batteries Nickel Cobalt Aluminum (NCA) batteries consist of nickel, cobalt, and aluminum, and are valued for their high energy density and long lives. The addition of aluminum improves the stability of the battery and increases its overall life. NCA batteries are primarily used by companies such as Tesla, especially in higher-performance vehicles, due to their high energy density at a relatively low weight. However, like NMC batteries, they are expensive to produce due to the cost of nickel and cobalt.

Lithium Manganese Oxide (LMO) batteries are made from lithium manganese oxide and are characterized by their thermal stability and safety. The spinel structure of manganese oxide allows for fast charging and discharging, making LMO batteries suitable for power tools and electric vehicles. However, LMO batteries have a lower energy density and a shorter life than other lithium-ion batteries, which limits their use in applications where long-term energy storage is critical.

Lithium Cobalt Oxide (LCO) batteries are made of lithium cobalt oxide and are commonly used in consumer electronics such as smartphones, laptops, and cameras. LCO batteries offer high energy density, which allows for compact battery sizes in portable devices. However, they have a relatively short lifespan and are prone to thermal instability, which can lead to safety concerns if not managed properly. The high cost and ethical concerns associated with the sourcing of cobalt are also challenges.

Solid-state batteries are an emerging technology that replaces the liquid or gel electrolyte found in traditional lithium-ion batteries with a solid electrolyte. This design promises several advantages, including higher energy density, improved safety, and longer life. Solid-state batteries are still in the development stage, but they have significant potential for future applications in electric vehicles and portable electronics, where they could offer improved performance and safety over current battery technologies.

Material vs. battery emissions

In this study, we use two units to talk about emissions:

1. CO₂e per kg when talking about the emissions of a battery active material (BAM)
2. CO₂e per kWh when talking about emissions from a finished battery

BAM emissions: As BAM is typically sourced by weight, this paper uses CO₂e per kg of BAM as the unit of measurement to reflect common sourcing practices in battery production.

Battery emissions: The overall emissions impact of batteries is measured in kg CO₂e per kWh to place emissions in the context of the end-use of the materials, such as in EVs. For EVs, batteries are typically sized by power capacity, e.g., an end user would buy a BEV with a 50kWh battery.

Linking the two emissions: The CO₂ emissions per kWh are calculated by first determining the amount (in kg) of each metal required to produce 1 kWh of battery capacity for both LFP and NMC811 batteries. The material composition is based on the reported bill of materials and stoichiometric calculations for these battery types. The CO₂ emissions per kWh are then calculated by multiplying the CO₂e emissions per kg of each metal by the amount of that metal required to produce 1 kWh of battery capacity.

Example calculation: Exhibit A and Exhibit B illustrate how CO₂ emissions for BAM were calculated, with the example of BAM for grey/black primary sourcing for NMC811 and LFP batteries. The same calculation method is used for all sourcing routes.

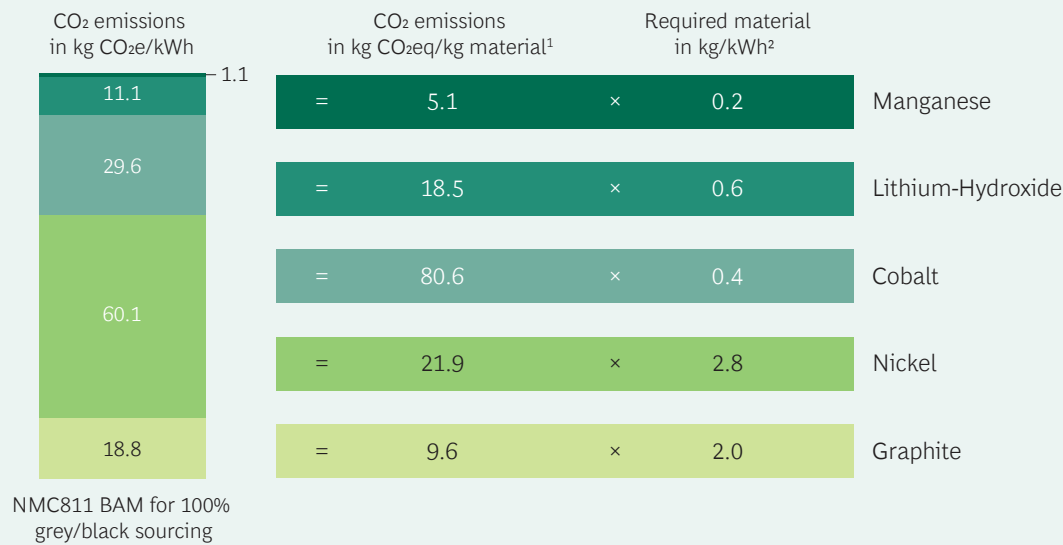
To estimate the emissions of a full EV battery, the respective battery power would be multiplied by the CO₂e emissions per unit of power, i.e., kWh:

Total CO₂e Emissions of an EV battery: Assuming the end user wants to purchase a BEV with a 50 kWh NMC811 battery, the total emissions would be 181.7 kg CO₂e per kWh × 50kWh = 9,085 kg CO₂e per battery



Material vs. battery emissions (cont.)

Exhibit A | Example calculation of CO₂ emissions for NMC811 grey/black sourcing

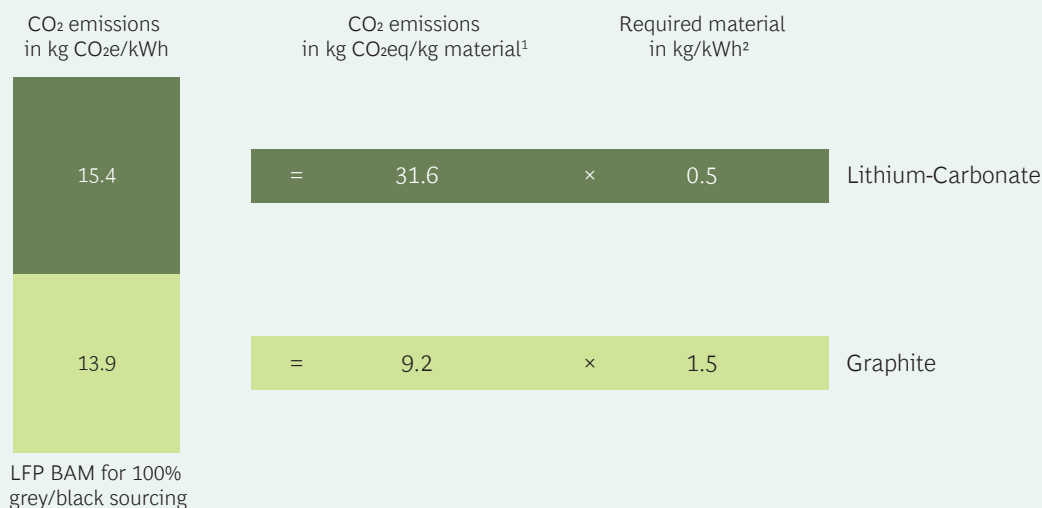


¹Emission for nickel and cobalt adjusted to reflect the battery chemicals, since the unit reference in literature and company reports given as kg metal in battery chemical

²Assumptions of 75 kWh battery with energy density 290 Wh/kg

Source: LCAs from academic studies or company websites, BOM from academic studies and Argonne Lab calculations, BCG Experts

Exhibit B | Example calculation of CO₂ emissions for LFP grey/black sourcing



¹Assumptions of 55 kWh battery with energy density 200 Wh/kg

Source: LCAs from academic studies or company websites, BOM from academic studies and Argonne Lab calculations, BCG Experts

More details on the BAM emissions estimation for the interested reader

The environmental impact of battery materials is assessed in terms of kg CO₂e per kg of metal or compound. The breakdown for the specific materials is as follows:

Nickel (Ni) and Cobalt (Co): The environmental impact of nickel and cobalt is quantified by measuring the CO₂ emissions (expressed in kg CO₂e) per kg of nickel or cobalt contained in their respective compounds, nickel sulfate (NiSO₄·6H₂O) and cobalt sulfate (CoSO₄·7H₂O). This approach provides an accurate representation of the "active" metal content within these compounds, consistent with common industry practices and methodological standards.

It is important to note that while this method is accurate, the CO₂ values must be normalized to reflect the emissions associated with the entire compound, not just the pure metal. As a result, there may be variations in the calculated emissions per kWh when applied to the overall battery production.

Lithium (Li), Manganese (Mn), and Graphite (C): The assessment is made in kg CO₂e per kg of Li₂CO₃, LiOH·H₂O, HPMSM (High Purity Manganese Sulfate Monohydrate), or graphite. This approach is employed because these materials are typically used directly in their compound forms, making the environmental impact of the entire compound more relevant.

Thus, by measuring kg CO₂e per kg of metal or compound, we can fairly compare the environmental impact of the actual metal content of different metals.

Emissions drivers: battery active material as major contributor to manufacturing emissions

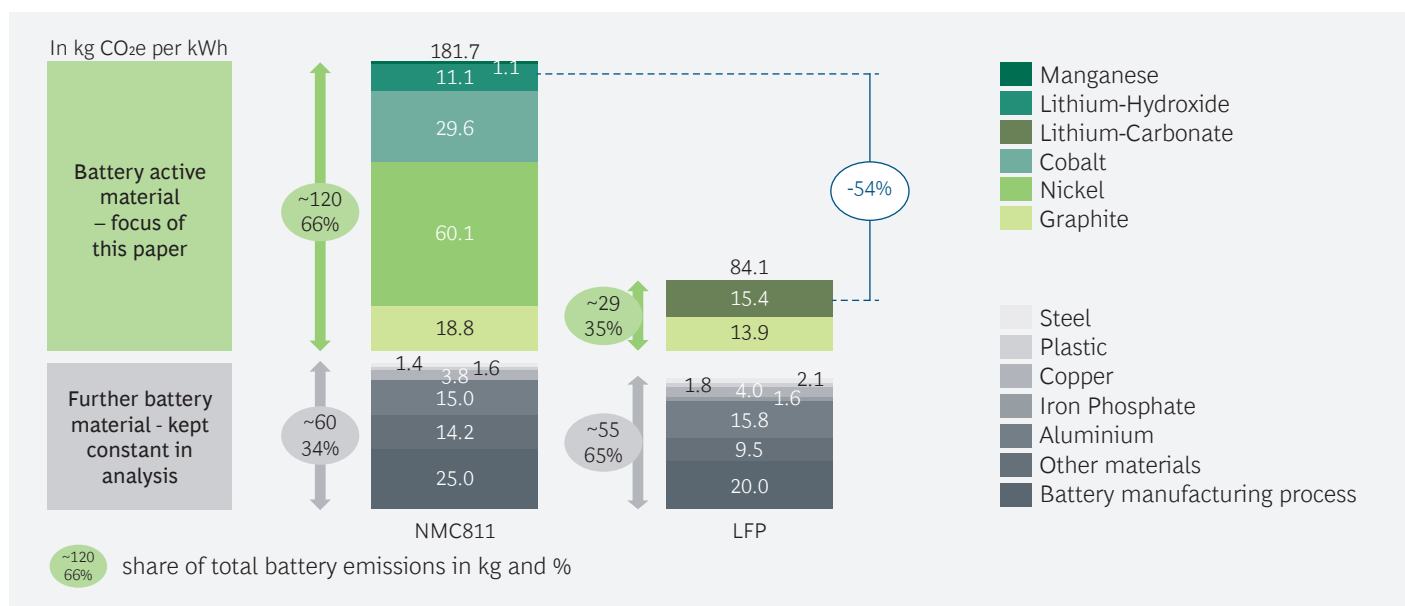
The main battery active materials are lithium, nickel, cobalt, manganese, iron, phosphate, and graphite.

On the cathode side, NMC batteries use lithium, nickel, manganese, and cobalt, while LFP batteries use lithium, iron, and phosphate. For both types of batteries, the anode side typically uses graphite and an electrolyte containing lithium to transfer electrons during charging and discharging. The current flows through copper (anode) and aluminum (cathode) foils, from the battery into the electric circuit of the EV or into the other direction when recharged.

Reducing emissions in battery production depends largely on five key materials—lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), and graphite, which are the main contributors to emissions due to energy-intensive extraction and processing. Other materials like copper and aluminum do not affect battery chemistry, and iron and phosphate have lower carbon footprints and limited recycling potential.

Decarbonizing these key materials can reduce emissions considerably, especially in NMC811 batteries, where active materials account for 66% of emissions. A 75 kWh NMC811 battery has a carbon footprint of approximately 180 kg CO₂e per kWh, due to the reliance on nickel and cobalt, which are more carbon-intensive to mine and process. LFP batteries have over 50% lower emissions than NMC811, around 85 kg CO₂e per kWh for a 55-kWh battery. LFP batteries have a lower footprint due to the use of more abundant, lower-emission materials like iron phosphate, which keeps emissions from BAM to only 35% of total battery emissions (see Exhibit 3).

Exhibit 3 | LFP batteries have a ~50% lower CO₂ footprint than NMC811 batteries



Assumptions: 1) Emissions sourced from CAM production and battery assembly is assumed as 20 kg CO₂/kWh for LFP and 25 kg CO₂/kWh for NMC 811. 2) 20 % material loss is assumed during CAM production. 3) Power of batteries assumed as 75 kWh for NMC 811 and 55 kWh for LFP battery.

Source: Literature review; company websites; Cylib; Abdelbaky et. Al; BCG Analysis

Details on the NMC811 and LFP BAM

NMC811 battery

The NMC811 battery was selected because of its high energy density, which means the battery can store a large amount of energy relative to its weight.

Lithium hydroxide ($\text{LiOH} \cdot \text{H}_2\text{O}$) also plays an important role in the NMC811 battery. Lithium hydroxide ($\text{LiOH} \cdot \text{H}_2\text{O}$), as opposed to lithium carbonate for LFP batteries, is preferred for the more powerful NMC battery. This choice allows for a more stable and higher-capacity crystal structure in the cathode, which is key to achieving the high energy density and long life that NMC811 batteries are known for.

Nickel sulfate ($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$) plays an important role in increasing the energy density of the battery. In NMC811 batteries, nickel makes up 80% of the cathode, allowing the battery to store more energy without increasing its size or weight. This is especially important for electric vehicles, which require powerful batteries without compromising on space. In addition, using more nickel reduces the need for cobalt, which is more expensive and has supply chain (ethical) challenges.

Cobalt sulfate ($\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$) is added to stabilize the battery chemistry for better energy density and a longer life. However, there is growing pressure to reduce or even eliminate cobalt from cathodes due to sourcing concerns, as most cobalt is mined in the Democratic Republic of Congo (DRC) and refined in China. In 2020, 69% of cobalt was mined in the DRC, and 67% of battery-grade cobalt sulfate was refined in China.¹ This concentrated route may face disruptions due to concerns over artisanal mining practices in the DRC and the risks associated with heavy reliance on China amid trade tensions. Artisanal mining refers to small-scale, often informal mining practices where workers extract cobalt in hazardous conditions with little to no safety measures.

Manganese sulfate ($\text{MnSO}_4 \cdot \text{H}_2\text{O}$) contributes to the stability and safety of the battery. It helps improve the thermal stability of the battery, reducing the risk of overheating and extending battery life. Manganese is more abundant and less expensive than cobalt, which helps keep production costs down while maintaining battery performance.

Graphite (C) is used as the anode material, as in LFP batteries. It is essential for storing and releasing lithium ions during the battery's charge and discharge cycles. Without graphite, the NMC811 battery would not be able to achieve the efficiency and reliability required for demanding applications such as electric vehicles, where consistent performance over many charge cycles is critical.

LFP Battery

LFP batteries are a smart choice for those looking to balance cost, durability, and environmental sustainability. They offer reliable performance using battery active materials that are easier to source and more affordable, making them suitable for a wide range of applications.

Lithium carbonate (Li_2CO_3) is the key ingredient in LFP batteries. It is responsible for storing and releasing energy, allowing the battery to efficiently power devices and vehicles. LFP batteries specifically use lithium carbonate (Li_2CO_3), which is essential for making the battery's cathode—the part of the battery that helps manage the flow of energy. The purity and availability of this lithium compound is critical because it directly affects how well and consistently the battery performs and how long it lasts.

Graphite (C) serves as the primary material for the battery's anode, the part where lithium ions are stored when the battery is not in use. Graphite's layered structure allows it to effectively store these ions and release them when needed, contributing to the battery's stability and ensuring smooth operation over time.

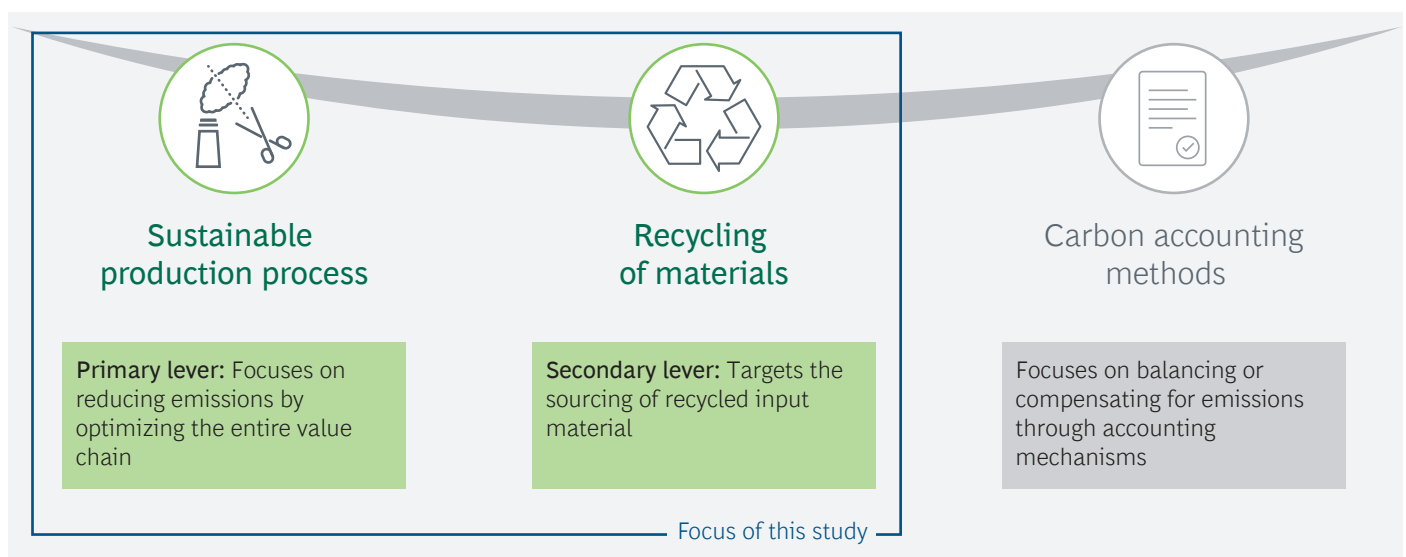
¹Das, J.; Kleiman, A.; Rehman, A.U.; Verma, R.; Young, M.H. "The Cobalt Supply Chain and Environmental Life Cycle Impacts of Lithium-Ion Battery Energy Storage Systems," Sustainability 2024, 16, 1910. <https://doi.org/10.3390/su16051910>

Decarbonization levers: two key levers to physically decarbonize active materials

Both LFP and NMC811 batteries require significant amounts of raw materials for battery active components.

The extraction and processing of these materials is energy-intensive and results in significant carbon emissions. These emissions can be reduced either by making the manufacturing process itself more sustainable (physically green), by recycling, or by balancing emissions through carbon accounting methods. This paper focuses only on the first two approaches—analyzing more sustainable sourcing options for production and recycling materials—because they directly address reducing emissions at the source (see Exhibit 4).

Exhibit 4 | Sustainable production processes and recycling reduce emissions at the source



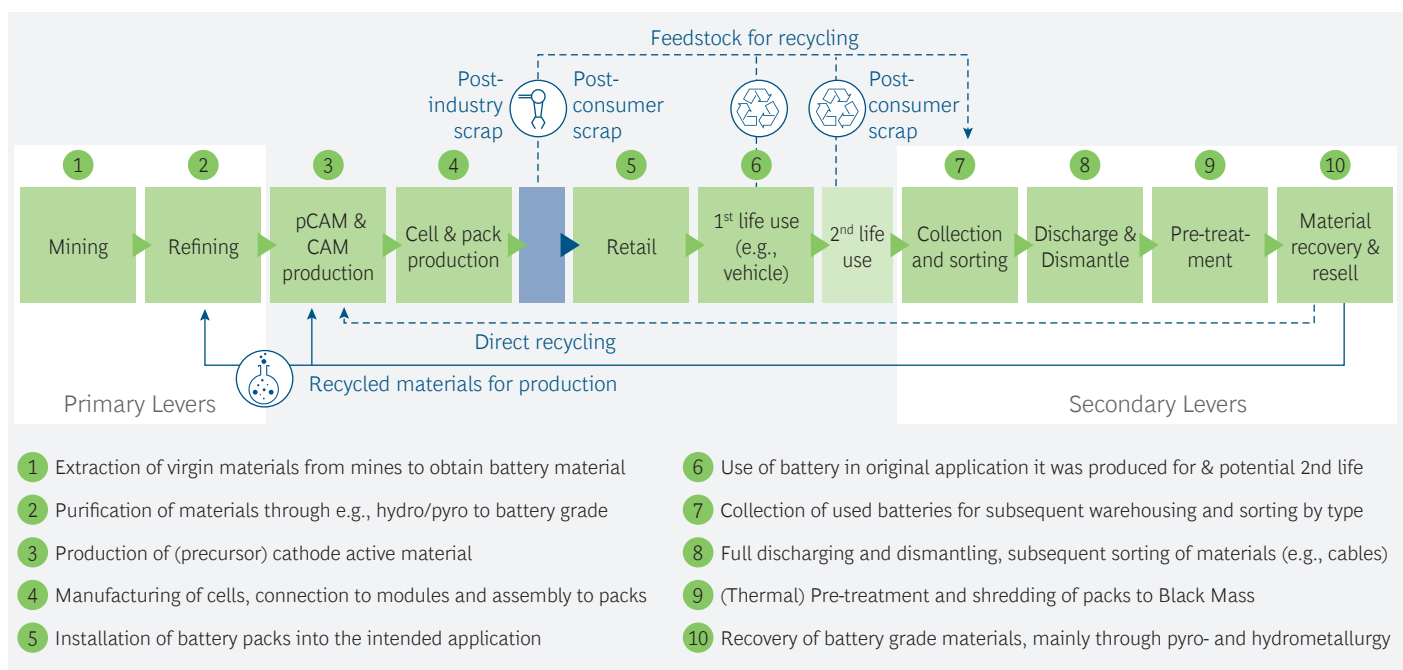
Source: BCG analysis

The primary reduction lever focuses on reducing emissions through sustainable supply-chain choices, specifically green primary sourcing. This approach involves sourcing raw materials from low-emission regions or using more environmentally friendly extraction and refining methods. Green sourcing has significant potential to lower emissions, especially for key materials like nickel, cobalt, and lithium. For example, sourcing lithium carbonate from South American brines or nickel from Scandinavia can drastically reduce emissions compared to high-emission sourcing alternatives more typical of other regions, such as China. However while reducing emissions through green primary sourcing holds great potential, all mining operations still have significant environmental and social impacts, highlighting the importance of ESG-compliant practices.

The secondary reduction targets advancements in recycling technologies. While direct recycling refers to the recovery of materials from end-of-life (EOL) batteries without extensive processing, hydrometallurgy and pyrometallurgy can effectively recover valuable materials from post-industry and post-consumer scrap through more intensive processes (see Exhibit 5). Hydrometallurgical (hydro) recycling, which uses chemical processes to extract metals, has high recovery rates for lithium, nickel, and cobalt and a low energy consumption. Pyrometallurgical (pyro) recycling, however, is a robust method suited for nickel and cobalt but generates higher carbon emissions due to its energy-intensive process and graphite burning. Emerging technologies like Early-Stage Lithium Recovery (ESLR) improve lithium recovery efficiency by extracting it early in the process, with the remaining materials processed using traditional techniques like pyro recycling. It can also be combined with hydrometallurgical processes (as German startup Cylib does), to enhance recovery rates and reduce emissions intensity. Alternatively direct recycling processes currently under development could be an interesting option especially for selected production waste or LFP batteries once they prove to be robust and work at scale.

Both levers can significantly reduce manufacturing emissions but face limitations due to resource availability and environmental impacts. For example, the Nordic countries offer more sustainable nickel sourcing, but their resources are limited and cannot alone meet the full demand in Europe. For the secondary lever, recycling is limited currently, because the main source is currently production scrap, as shown in BCG's study "Striking Gold with EV Battery Recycling" (2023). This challenge is intensified by recent findings showing that today's batteries can already outlive the EV itself, further limiting the availability of secondary materials and requiring recycling to focus mainly on production waste. However, as EV batteries reach the end of their life cycle and enable the use of used batteries in addition to production scrap, recycling will gain importance, especially with the EU Battery Regulation mandating recycling targets by 2031 to ensure sustainable production. Understanding how to both source and recycle these materials, and the impact of each approach on emissions, is critical.

Exhibit 5 | Primary and secondary levers address different stages of the value chain

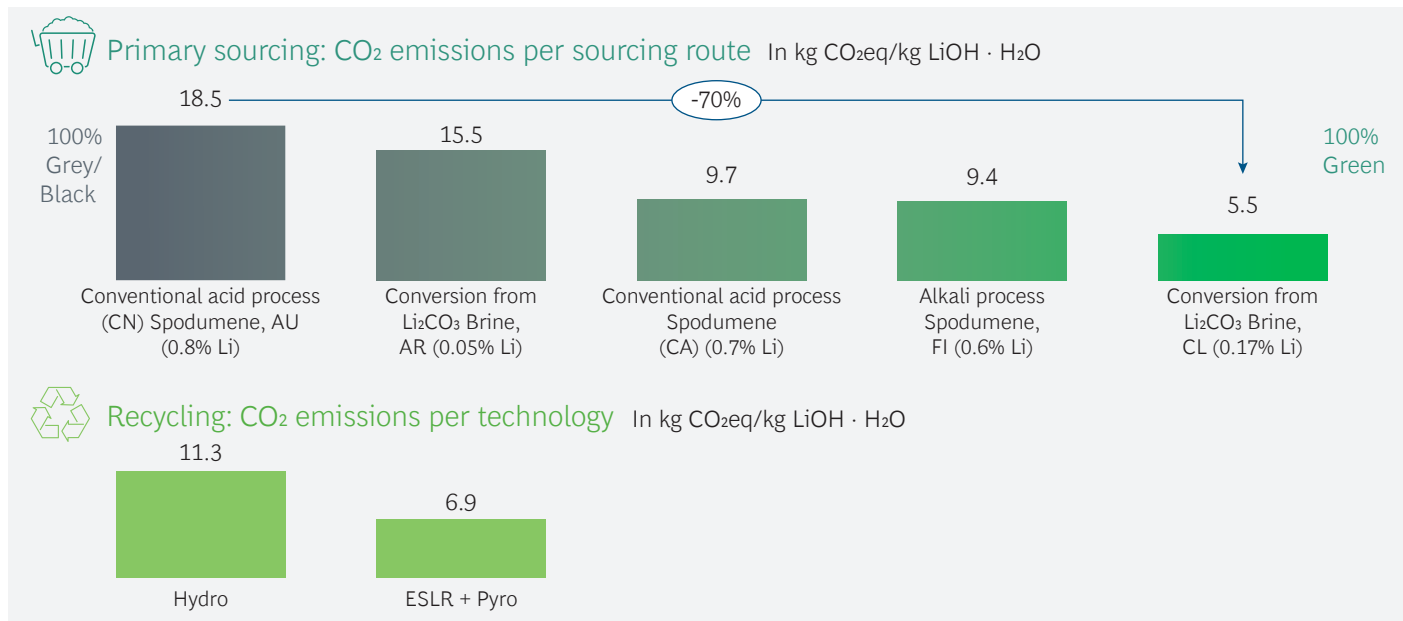


Source: Expert interviews, BCG analysis

Measuring the impact: CO₂ emissions in primary sourcing and recycling

This section delves deeper into the CO₂ emissions associated with each decarbonization approach, focusing on key BAM. A comparative analysis was conducted for several primary sourcing and recycling routes for each material, using lithium hydroxide as an example (see Exhibit 6).

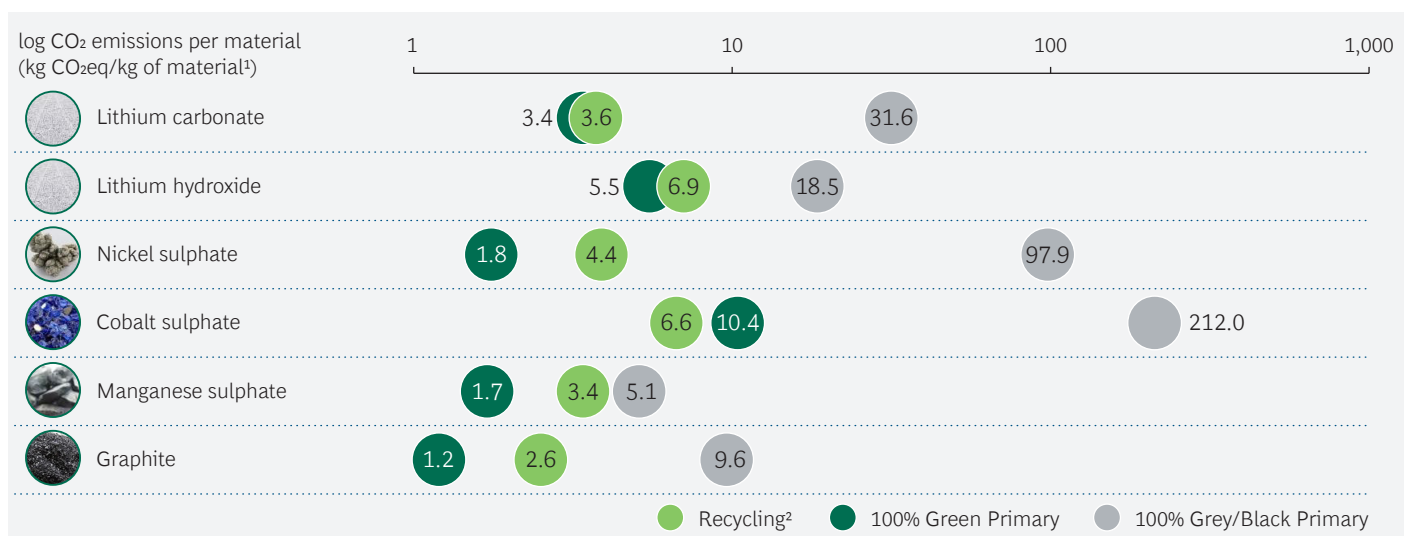
Exhibit 6 | Up to ~70% reduction potential for lithium hydroxide



Source: Kelly et al. 2022, Chordia et al. 2023, Abdelbaky et al. 2023, Cylib, BCG analysis

For this paper, however, we highlight the results of 100% grey/black primary sourcing and 100% green primary sourcing, as well as the lowest emission recycling method, in order to showcase the greatest opportunities for emissions reduction (see Exhibit 7).

Exhibit 7 | Carbon footprints of BAM vary for primary sourcing and recycling methods



¹For nickel measured in kg CO₂eq / kg Ni in NiSO₄, for cobalt in kg CO₂eq/kg Co in CoSO₄·7H₂O ²ESLR + Pyro for Lithium, Hydro for the remaining materials; even higher reduction potential once recycling technologies evolve further

Source: Academic journals, life cycle assessments, BCG analysis

Lithium carbonate (Li_2CO_3)

Lithium carbonate, mainly used in LFP batteries, is cost-effective and ensures stable performance. The two main lithium sources for primary sourcing, brines and spodumene, differ in extraction and emissions. Brines are saltwater solutions evaporated to concentrate lithium, while spodumene is a lithium-rich mineral requiring more energy-intensive mining and processing.

Lithium carbonate from grey/black primary sourcing, particularly from Chinese brines, carries a significantly high carbon footprint of $31.6 \text{ kg CO}_2\text{e/kg Li}_2\text{CO}_3$ ¹, primarily due to a lower lithium concentration and hence more energy-intensive processing. On the other hand, sourcing from Chilean brines reduces this footprint drastically to $3.4 \text{ kg CO}_2\text{e/kg Li}_2\text{CO}_3$ ¹, benefiting from more carbon-efficient processes. Future so called direct lithium extraction can offer additional reduction potential.

Recycling through a combination of ESLR and pyro recycling could potentially provide the highest reduction, reducing emissions to $3.6 \text{ kg CO}_2\text{e/kg Li}_2\text{CO}_3$, as it combines thermal pre-treatment, grinding, and water leaching to efficiently extract lithium while improving the recovery and purity of other materials.

Lithium hydroxide ($\text{LiOH}\cdot\text{H}_2\text{O}$)

Lithium hydroxide, mainly used in NMC batteries, can be produced through methods similar to lithium carbonate but requires additional conversion and purification steps. Lithium hydroxide from grey/black primary sources, sourced from an Australian spodumene and processed with conventional acid leaching in China, results in $18.5 \text{ kg CO}_2\text{e/kg}^2$. The use of traditional acid leaching, typically producing high emissions, can achieve lower levels when powered by clean energy, as seen in Canada. The greenest primary sourcing option, however, is sourcing from carbon-efficient Chilean brines, which cuts emissions to $5.5 \text{ kg CO}_2\text{e/kg}^2$.

Similar to lithium carbonate, recycling with ESLR and pyro offers high reduction potentials, as it cuts emissions to $6.9 \text{ kg CO}_2\text{e/kg}$.

Nickel sulphate ($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$)

Nickel sulfate is produced from sulfide ores and laterite ores, each with distinct processes and emissions. Sulfide ores, containing nickel and sulfur, are processed through pyrometallurgy, where the ore is crushed, melted into nickel matte, and refined into nickel sulfate. Sulfur content in the ore lowers the carbon footprint simply by reducing fuel requirements, but global sulfide ore reserves are limited.

In contrast, laterite ores, lacking sulfur but containing more oxygen, require more energy-intensive methods like High Pressure Acid Leaching (HPAL) and Rotary Kiln Electric Furnace (RKEF). HPAL dissolves nickel using high pressure and sulfuric acid, while RKEF melts the ore to produce nickel pig iron or ferronickel, later refined into matte and finally to nickel sulfate.

Nickel sulfate produced from laterite ores in grey/black primary sourcing, such as when mined in Southeast Asia and processed in China using RKEF methods, results in the worst case in a high carbon footprint of up to $97.9 \text{ kg CO}_2\text{e/kg Ni}$ in $\text{NiSO}_4\cdot 6\text{H}_2\text{O}$ ³ due to increased energy requirements and the chemical reactions involved. In contrast, green primary sourcing from sulfide ores in regions like Finland can reduce emissions drastically to $1.8 \text{ kg CO}_2\text{e/kg Ni}$ in $\text{NiSO}_4\cdot 6\text{H}_2\text{O}$ ⁴, benefiting from more efficient bio heap-leaching technologies.

Regarding recycling, hydro recycling offers the most sustainable alternative, lowering emissions to $4.4 \text{ kg CO}_2\text{e/kg Ni}$ in NiSO_4 . This would consider that the graphite is recycled and not burned as assumed in this paper.

¹V. Schenker et al. "Regionalized life cycle assessment of present and future lithium production for Li-ion batteries" Resources, Conservation and Recycling, 2022. <https://doi.org/10.1016/j.resconrec.2022.106611>.

²M. Chordia et al. "Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene" Resources, Conservation and Recycling, 2022. <https://doi.org/10.1016/j.resconrec.2022.106634>.

³Tijsseling, L.T., Whattoff, P.W. "Product carbon footprint of nickel sulfate hexahydrate" VDA - Minviro Life Cycle Assessment, 2023.

⁴Company PCF

Cobalt sulphate (CoSO₄·7H₂O)

Cobalt can be obtained as a by-product of nickel refining from laterite ores, involving energy-intensive processes. In grey/black sourcing, cobalt is produced alongside nickel using the RKEF process, resulting in a high carbon footprint of 212 kg CO₂e/kg Co in CoSO₄·7H₂O⁵ due to the lower cobalt content of the region's ores, which requires more energy to process. Potentially counterintuitive, 100% green primary sourcing involves sourcing from DRC and refinement in China, which reduces emissions to 10.4 kg CO₂e/kg Co in CoSO₄·7H₂O⁵. This is mainly due to the higher cobalt content of the DRC ore as well as economies of scale and more efficient processes in China. However, ethical concerns regarding artisanal mining in the DRC must be considered.

Lastly, hydro recycling is particularly efficient for cobalt and hence offers the greatest decarbonization potential of all three options, with emissions reduced to 6.6 kg CO₂e/kg Co in CoSO₄·7H₂O.

Manganese sulphate (MnSO₄ · H₂O)

Manganese is essentially used in the form of High-Purity Manganese Sulfate Monohydrate (HPMSM), contained in lithium-ion battery cathodes to enhance energy storage and lifespan. The production process typically involves hydrometallurgical extraction, where manganese ore is dissolved in an acidic solution and then purified through electrolysis.

In China, manganese sulfate production via grey/black primary sourcing generates the highest carbon footprint of 5.1 kg CO₂e/kg HPMSM⁵, largely due to the dependence on coal-powered energy for hydrometallurgical extraction. In contrast, green primary sourcing from Australia, followed by refining in the US., drastically reduces emissions to 1.7 kg CO₂e/kg HPMSM⁵, owing to the higher ore quality and use of the low-carbon energy grid in Australia.

Manganese is typically recycled via hydro recycling, which can reduce emissions to 3.4 kg CO₂e/kg.

Graphite (C)

Graphite is sourced either naturally or synthetically. Natural graphite is mined and processed for cost-efficient standard batteries. Synthetic graphite, produced via the energy-intensive Acheson process, offers high purity and consistency for high-performance batteries. However, recent developments in Norway aim to reduce synthetic graphite emissions even further by using renewable energy, adapting a closed-furnace system that minimizes energy consumption and integrates recycling throughout the production cycle. The 100% green sourcing route contains natural graphite mined in Canada, reducing the carbon footprint to 1.2 kg CO₂e/kg⁵, due to low-emission extraction processes. In contrast, natural graphite mining in China generates emissions approximately eight times higher, reaching 9.6 kg CO₂e/kg⁶.

Similar to manganese, the recycling method used for graphite is hydro recycling. Emissions with hydro recycling can be reduced to 2.6 kg CO₂e/kg.

Key takeaways

Primary sourcing and recycling both offer key opportunities to reduce CO₂ emissions in the battery supply chain. Green primary sourcing can lower emissions considerably, with materials like nickel and cobalt showcasing reduction potentials of over 90%. ESG-driven business decisions can create the potential for a shift from gray/black sourcing to greener sourcing. Similarly, conventional recycling methods like pyro or hydro recycling can cut emissions by up to 90% for some materials and have considerable potential as recycling technologies further evolve. ESLR, for example, can be combined with hydro recycling processes, as implemented by the German recycling startup Cylib, which can further increase recovery rates while decreasing emissions. As both primary and secondary levers face limitations, a combined approach of green primary sourcing and expanded recycling is essential to ensure a sustainable supply and emissions reduction.

⁵Company LCA

⁶P. Engels et al. "Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data" *Journal of Cleaner Production*, Volume 336, 2022, <https://doi.org/10.1016/j.jclepro.2022.130474>.

Bringing it together: emissions reduction potential depends on sourcing and battery type

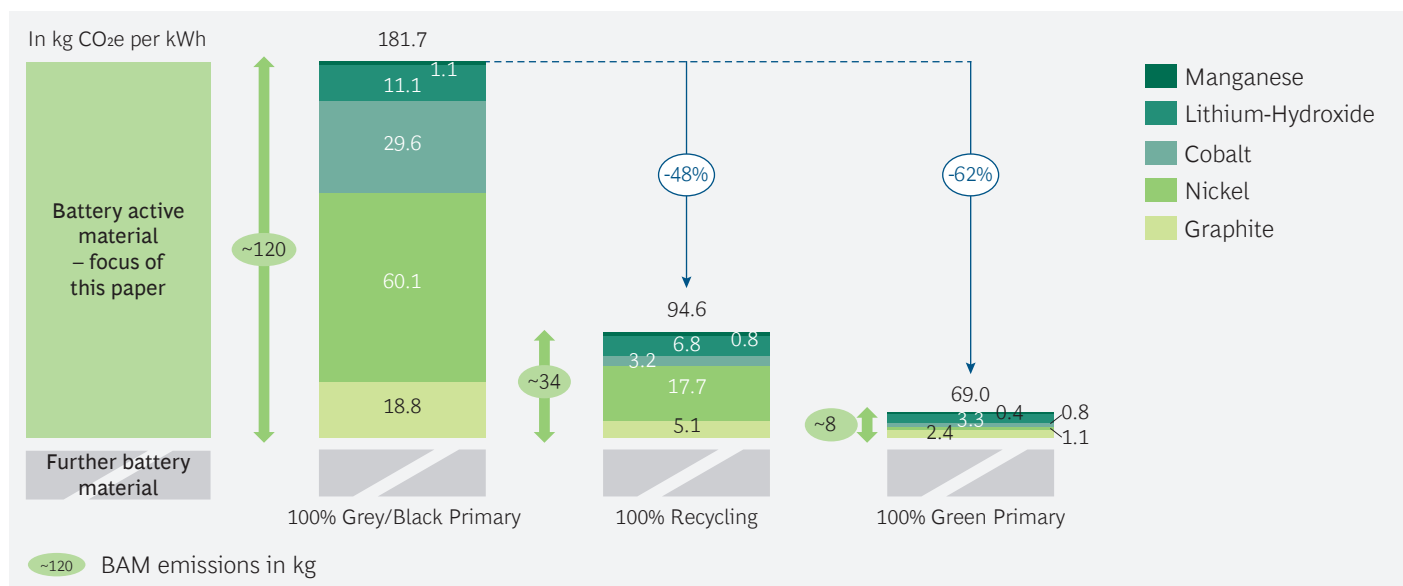
Our analysis shows that the carbon footprint of the core BAM—lithium, nickel, cobalt, manganese, and graphite—depends significantly on the approach to primary materials sourcing and the extent recycled materials are used. The full decarbonization potential, regarding BAM, also varies between NMC811 and LFP batteries, as the amount of each material in these batteries differs.

For both battery types, surprisingly, the greenest primary sourcing options can provide lower emissions than recycled materials. However, the availability of primary sourcing materials is limited, and 100% green primary sourcing reflects a fully optimized value chain, where all processes are sustainable. In contrast, the recycling scenario represents conventional recycling, a base case that still relies on non-green inputs such as conventional chemicals and electricity, meaning significant potential exists for further emissions reduction as greener technologies are implemented. This underscores the need for a balanced approach that includes both recycling and sustainable primary sourcing to meet future demand while minimizing environmental impact.

For NMC811 batteries, we see the highest emission reduction potential of up to 62% by sourcing 100% green active materials. This is mainly driven by reducing emissions from nickel, cobalt and graphite (see Exhibit 8). While this seems promising, the availability of these resources in the respective locations is limited and the effort required to obtain them is often high.

For recycled materials, the maximum emission reduction potential is about 48%. Like the use of 100% green primary materials, the availability of secondary resources will remain limited for years to come. According to BCG's "Striking Gold with EV Battery Recycling" (2023), at most ~19% of nickel demand in Europe can be met by recycled materials in the short term.

Exhibit 8 | Up to ~48% CO₂ reduction via recycling and ~62% via green primary for NMC811

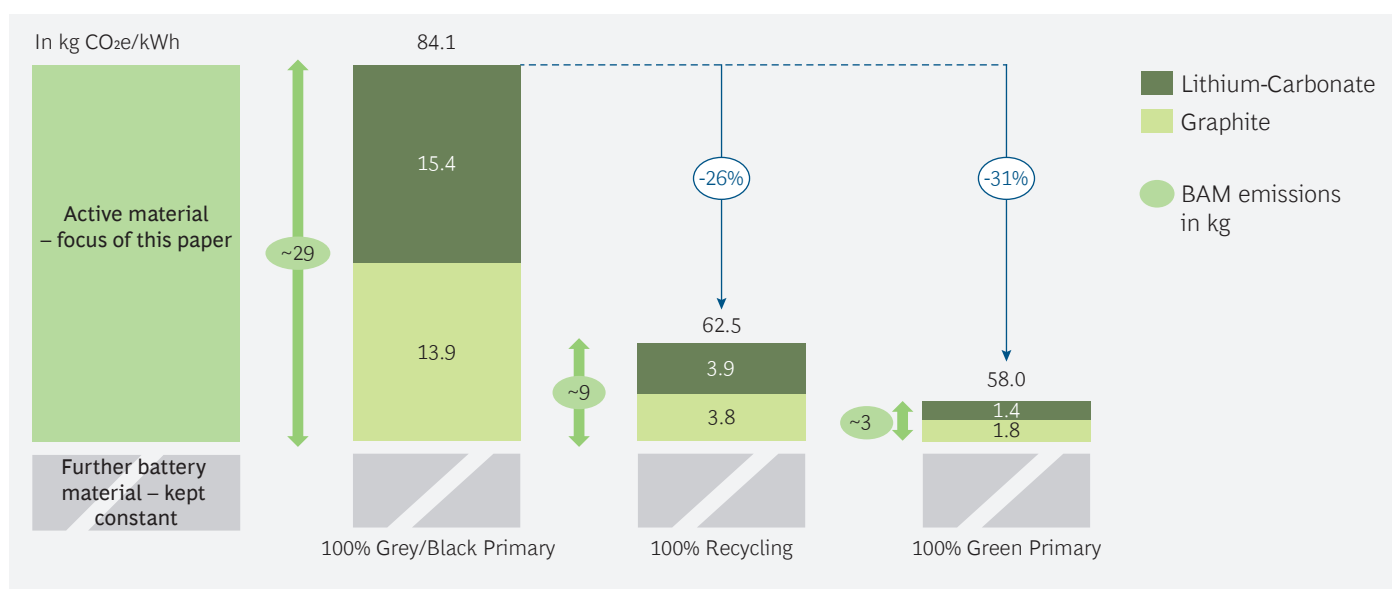


¹Average of hydrometallurgical and pyrometallurgical recycling; Note: Emissions sourced from cell and pack assembly is assumed as 20 kg CO₂/kWh and constant for all scenarios, all battery packs are assumed to be 75kWh and total car weight is assumed as 500 kg

Source: Literature review; company websites; Cylib; Abdelbaky et. Al; BCG Analysis

For LFP batteries, the emissions reduction potential is significantly lower, partly due to the lower share of BAM in LFP batteries compared to NMC811. In LFP batteries, up to 31% emissions reduction is achievable by using 100% green primary materials, while up to 26% is possible by using only recycled materials. However, the lower value of the materials used in LFP batteries can make recycling challenging considering the processing cost. In both cases, the main driver is the reduction of graphite production emissions (see Exhibit 9). However, the same material scarcity constraints apply as for NMC811 batteries.

Exhibit 9 | Up to ~26% CO₂ reduction via recycling and ~31% via green primary for LFP



Note: Emissions sourced from CAM production and battery assembly is assumed as 20 kg CO₂/kWh for LFP and 25 kg CO₂/kWh for NMC 811, battery packs are assumed to be 55 kWh for LFP and 75kWh for NMC 811 and total car weight is assumed as 500 kg

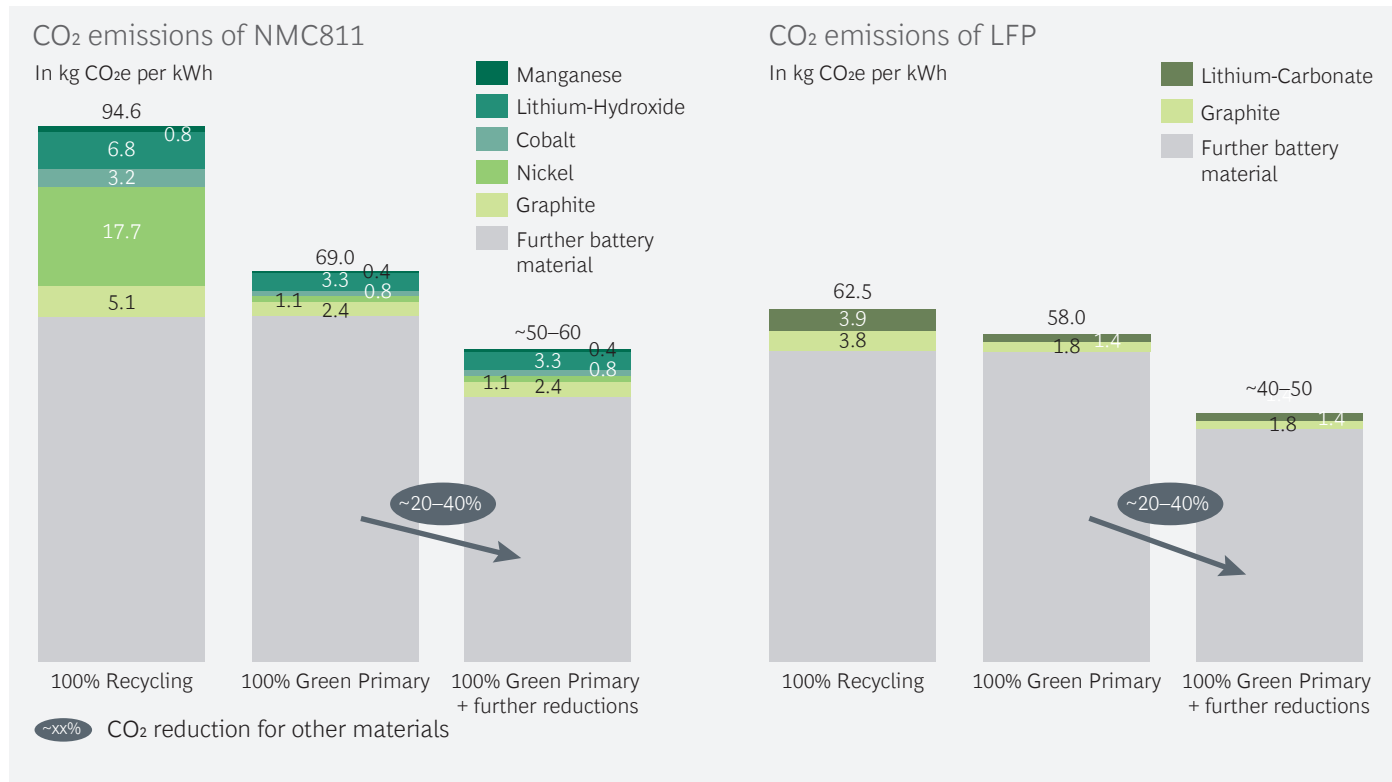
Source: Literature review; company websites; Cylib; Abdelbaky et. Al; BCG Analysis

While all of this will go far toward reducing carbon emissions from battery manufacturing, there are additional opportunities that have not been addressed in our analysis:

Non-active materials offer additional potential to reduce battery production emissions by up to 20%–40% for each material for LFP and NMC811 batteries (see Exhibit 10). This is particularly significant for LFP batteries, where non-active materials contribute approximately 65% of total production emissions. While the specific strategies to achieve these reductions are beyond the scope of this paper, they warrant further investigation.

Extending battery life through second-use applications is key to improving overall sustainability. When EV batteries reach the end of their 10-to-15-year lifespan, they can be repurposed for stationary storage applications, potentially providing an additional 15–25 years of service. This approach maximizes the utility of batteries and significantly improves their end-to-end environmental impact, although it may also delay the availability of secondary materials for recycling, potentially reducing the immediate supply for material recovery processes.

Exhibit 10 | Decarbonizing other battery materials could unlock further reduction potential



Note: Emissions sourced from CAM production and battery assembly is assumed as 20 kg CO₂/kWh for LFP and 25 kg CO₂/kWh for NMC 811, battery packs are assumed to be 55 kWh for LFP and 75kWh for NMC 811 and total car weight is assumed as 500 kg

Source: Literature review; company websites; Cylib; Abdelbaky et. Al; BCG Analysis

Implications for decision-makers

Given the limited availability and higher cost of green primary and secondary resources, companies must strategically align sourcing decisions with their emissions reduction goals.

For those that prioritize minimal carbon footprints, choosing the lowest-emission materials is critical. While some may choose to reduce costs even if it means accepting higher emissions, such extremes will likely be rare. Most companies will find themselves in the middle, using a mix of green primary sourcing, recycling, and conventional materials to balance their specific goals and constraints. Therefore, it is vital for stakeholders, from the beginning of the supply chain through to industry investors and policy makers, to thoroughly understand sourcing options, available technologies, and the impact on the overall carbon footprint.

1 Understanding the opportunity landscape is crucial. BAM contribute significantly to emissions, particularly in NMC batteries, where they are responsible for 66% of the total CO₂e production emissions per kWh, compared to 35% for LFP batteries. By understanding the emissions contribution of different materials and technologies, stakeholders can pinpoint areas for impactful emission reduction.

- **Automakers** should identify customer groups interested in green and then map out the best opportunities to reduce emissions by forming partnerships with battery manufacturers to optimize the sourcing of BAM.
- **Battery manufacturers** should collaborate closely with customers who value low-emissions batteries to develop transparent sourcing strategies that prioritize low-emission materials, helping to reduce the carbon footprint of batteries.
- **Policy makers** need to promote transparency in the emissions associated with battery materials and create incentives for decarbonization through targeted industrial policies.

2 Leveraging both primary sourcing and recycling is essential. Decarbonization of BAM requires a dual approach, combining green primary sourcing with effective recycling strategies, as the availability of green primary and secondary materials and capacity may be limited in the future. So, while green sourcing can have more impact, recycling is also essential to reach long-term emission goals.

- **Mining and refining companies** should also understand which of their customers are interested in green materials and invest in low-emission extraction methods or adopt green mining practices to serve those and significantly reduce primary emissions.
- **Battery manufacturers**, after identifying which of their customers are interested in green batteries, need to advance recycling technologies and develop strategic partnerships with recyclers to ensure a steady supply of sustainable materials.
- **Policy makers** can support regulations that encourage the use of recycled materials in battery production and promote the adoption of green sourcing methods to drive decarbonization.

3 Building sourcing capacity in low-emission regions is key to reducing global battery emissions. For NMC batteries, a reduction of about 60% of BAM production is possible through green sourcing, and about 30% for LFP batteries. For individual materials, emissions reductions of >90% are possible. While BAM's primary emissions reduction potential is significant, the supply of green materials will be limited and competition for them intense. Building sourcing capacity in areas that enable cleaner primary materials can therefore be a critical emissions reduction lever.

- **Mining and refining companies**, to serve their green-interested customers, should focus on sourcing in regions with lower carbon footprints to align with global decarbonization goals.
- **Battery manufacturers** should establish long-term contracts with suppliers in low-emission regions to ensure a sustainable supply chain and enable greener batteries for interested customer segments.
- **Industry investors** can identify and fund sourcing opportunities in low-emission regions, supporting long-term sustainability.

4 Recycling infrastructure must be strategically located and grow in line with demand. Recycling can reduce emissions by up to 50% for NMC batteries and up to 25% for LFP. Facilities must be positioned in the right locations to optimize partnerships with customers and meet evolving demand. Strategically located recycling will ensure efficiency, reduce costs, and handle end-of-life (EOL) battery volumes.

- **Mining and refining companies** should engage their sustainability-conscious customers to identify critical locations for their recycling facilities and anticipate demand developments.
- **Battery manufacturers** should collaborate with recyclers to establish facilities in strategic locations that align with recycled material supply and needs of customers who value green battery materials.
- **Policy makers** can encourage the development of recycling infrastructure in regions that support sustainable battery ecosystems and align with demand projections.

5 Securing secondary materials is essential as supply constraints increase. Recycling is the greenest option for some BAM and plays a key role in emissions reduction, though not always matching the reduction possible with sustainable primary sourcing. Recycling can reduce emissions by up to ~50% for NMC811 and up to ~25% for LFP batteries. While expected to contribute only 10%-20% of total BAM supply by 2030, the scarcity of green primary and secondary BAM makes recycling a necessity. As demand rises and primary green materials remain scarce, securing secondary materials from EOL batteries and scrap is critical.

- **Battery manufacturers** should strengthen partnerships with recyclers to ensure access to secondary materials and stabilize supply chains to optimally serve customers that value green batteries with recycled materials.
- **Automakers** can advocate for stronger recycling initiatives and establish closed-loop partnerships to ensure the availability of materials for future production.
- **Policy makers** can implement policies that drive secondary material recovery and reuse, reducing reliance on new raw materials.

In summary, companies that successfully navigate this complex landscape can seize the opportunity to strategically source materials and not only reduce their carbon footprint but lead the way to a more sustainable future for the battery industry and beyond.

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