



# Towards sustainable extraction of technology materials through integrated approaches

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**Abstract** | The transition to a low-carbon economy will be material-intensive. Production of these materials (from mining to manufacturing) incurs environmental costs that vary widely, depending on the geology, mineralogy, extraction routes, type of product, purity of product, background system or manufacturing infrastructure. Understanding the impacts of the raw materials underpinning the low-carbon economy is essential for eliminating any dissonance between the benefits of renewable technologies and the impacts associated with the production of the raw materials. In this Review, we propose an integrated life cycle assessment and geometallurgical approach to optimize the technical performance and reduce the environmental impact of raw material extraction. Life cycle assessments are an effective way of understanding the system-wide impacts associated with material production, from ore in the ground to a refined chemical product ready to be used in advanced technologies such as batteries. In the geometallurgy approach, geologists select exploration targets with resource characteristics that lend themselves to lower environmental impacts, often considering factors throughout the exploration and development process. Combining these two approaches allows for more accurate and dynamic optimization of technology materials resource efficiency, based on in situ ore properties and process simulations. By applying these approaches at the development phase of projects, a future low-carbon economy can be achieved that is built from ingredients with a lower environmental impact.

The transition to renewable energy, especially the electrification of transportation systems, will require a notable quantity of technology metals and materials<sup>1,2</sup>. The transition from internal combustion engine vehicles to electric vehicles (EVs), along with the deployment of solar photovoltaic and wind power, are considered three major technologies for decarbonization<sup>3</sup> (FIG. 1). Access to raw materials that enable these technologies, termed here as ‘technology materials’, is critical to the energy transition. However, the systems that deliver these engineered materials come with local and global pressures on the environment. These impacts need to be quantified and, wherever possible, mitigated<sup>4</sup>. It is also essential that the environmental impact of extracting, processing, refining and embedding these raw materials in the low-carbon economy does not limit the impact reduction of the technology itself or substantially displace impacts to other regions or impact categories. The social and governance issues for the production of these raw materials can also be significant and can be challenging to resolve<sup>4,5</sup>.

There is a strong consensus that the demand for technology materials required for the energy transition will increase substantially in the 2020s. For example, between 2015 and 2050, global EV stock is estimated to increase from 1.2 million to 965 million passenger cars, and battery storage capacity will increase from 0.5 gigawatt-hours to 12,380 gigawatt-hours<sup>6</sup>. Some have claimed that the extractive industry will face challenges adapting to this rapid increase in demand<sup>7–11</sup>. Therefore, it is vital to understand how mineral deposit characteristics can influence environmental impacts as new projects advance over the coming decades<sup>12</sup>.

Lithium-ion batteries (LIBs) are currently the dominant technology for energy storage in EVs<sup>13</sup>. They can contain a combination of lithium, cobalt, manganese, aluminium, iron and nickel in the cathode and graphite in the anode, as well as aluminium and copper in other pack components (FIG. 1a). A range of competing battery cell chemistries dictate the proportion and form of the materials required. Current estimates indicate that growing demand for LIBs will mean demand for the necessary

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## Key points

- The 2020s will see substantial demand growth for lithium, cobalt, nickel, graphite, rare-earth elements, manganese, vanadium and other materials, due to the transition to renewable energy.
- Production of battery grade or equivalent purity technology metals can have an extensive range of climate change and environmental impacts.
- The impacts of technology material production are rooted in geology. Consideration of geology and mineralogy allows a better understanding of the main drivers for technical recovery (both gangue and ore), which influences the process routes needed to manufacture technology materials.
- Different process routes have different environmental impacts, which can be quantified and compared using life cycle environmental impact methodologies.
- Life cycle assessment can be used to uncover hotspots in the development phase for mitigation before new operations are built.

materials will grow by factors in the range 18–20 for lithium, 17–19 for cobalt, 28–31 for nickel and 15–20 for most other technology materials from 2020 to 2050 (REF.<sup>14</sup>).

The battery represents over two-thirds of the life cycle carbon footprint of a manufactured EV. The impacts of extracting, processing and refining the raw materials for the cathode and anode contribute to 46% of the battery impact at 33.9 kg CO<sub>2</sub> eq. per kilowatt-hour for an NMC111 chemistry battery<sup>15,16</sup>. However, certain data used within life cycle assessment (LCA), such as graphite and lithium data, likely underestimate the impact of battery material production. Other battery types with different material demands also have potential to be more widely used in the future, for example, the vanadium flow battery<sup>17</sup>.

Rare-earth elements (REEs) have an array of applications, from large neodymium (Nd)–iron (Fe)–boron (B) magnets in offshore wind turbines and EV power trains (FIG. 1), to use in catalysts, ceramics, phosphors and medicine<sup>18</sup>. REE magnets are more suitable for these applications because the magnetic energy product of REE permanent magnet material is higher than that of ferrite and Al–Ni–Co permanent magnet materials<sup>19,20</sup>. Demand for Nd oxide and praseodymium (Pr) oxide is forecast to increase by 4.7% per year between 2016 and 2026, owing to growth in EVs and wind turbines<sup>21,22</sup>.

The markets for major metals such as copper, nickel and aluminium are already very large (millions and billions of tonnes per year), so increasing demand for EVs will have a smaller percentage impact on overall demand<sup>23–25</sup>. However, the specialist raw materials used to make the cathode and the anode of the battery are currently relatively small markets (thousands of tonnes), so they will be substantially impacted by growing demand from EVs.

In this Review, we give an overview of the methods that can quantify the environmental impacts of technology materials production. We discuss the key features and qualitative environmental credentials of REE, Li, Co, Ni, Mn, V and graphite deposits, before showing how quantitative geometallurgy–LCAs can be conducted from exploration to mining, processing, refining and manufacturing, so that the environmental impact can be assessed. While only a selection of technology materials (REEs, Li, Co, Ni, Mn, graphite, V) are included in this Review, it should be noted that the rapid evolution of

technology and material substitution means that many more materials will fit the criteria of technology materials in the future. A discussion of the social and governance issues related to the production of technology materials is beyond the scope of this Review, but is an essential subject for continued research.

## Technology and resources

This section provides an overview of how technology materials get from a mine to being embedded in low-carbon technology.

### Production stages

Moving elements from ore in the ground to the EV manufacturing industry requires several distinct steps, from extracting and processing the raw material to manufacturing chemicals that match the specifications required for applications in battery manufacturing or Nd–Fe–B magnet formation. The various stages can occur in different parts of the world and have different impacts. The specific route materials take can be determined by the mineralogy of the raw material in question and the desired output product. However, production of all materials commonly share the same phases of exploration, extraction (usually mining), beneficiation and mineral processing, and production or refining (FIG. 2), followed by the manufacture of components.

### Purity and chemistry

The technologies used in the low-carbon economy demand high-purity materials with specific chemistry. However, producing these high-purity materials requires additional energy inputs and deposit characteristics that can influence the environmental impacts of production.

EVs' performance and safety requirements dictate that technology materials embedded in the power train and within the LIBs must have sufficient purity<sup>16,26</sup>. For example, in power trains, high oxygen concentrations in the rare-earth metal can reduce the intrinsic coercivity of the rare-earth permanent magnet, and, therefore, impact performance<sup>27</sup>. The purity of rare-earth metals should exceed 99.95% when used as ingredients in permanent magnetic materials<sup>28,29</sup>.

The LIBs of an EV contain various components, including a cathode, an anode, separators, electrolytes, current collectors, casing and other components<sup>30</sup>. The lithium, nickel, cobalt and other materials used in batteries require specific physical and chemical properties to ensure high energy and power density (TABLE 1). Most importantly, battery manufacturers frequently require higher purity chemicals for their products than were historically required in other industries<sup>30–32</sup>. Battery quality materials often require additional steps in processing, which can be energy-intensive and materials-intensive, increasing the direct and embodied environmental impacts associated with that processing method<sup>33</sup>. Besides absolute purity, upper limits on impurity concentrations, such as magnetic impurities, are critical to ensure the high functioning of the battery over many cycles of charging and recharging<sup>33</sup>. Particle size distribution and morphology of different chemical feedstocks are also critical, and the requirements

### Technology materials

Any material that is in demand, available and used for the purposes of furthering technology and engineered systems.

### Carbon footprint

The amount of carbon dioxide released into the atmosphere as a result of the activities of a product or process.

### Life cycle assessment

(LCA). A methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process or service.

### Power trains

Mechanisms that transmit the drive from the engine of a vehicle to its axle.

### Battery quality

A specification for chemical products, usually implying low impurity concentrations and adequate particle size distribution, that indicates that the product can be used to make advanced battery components.

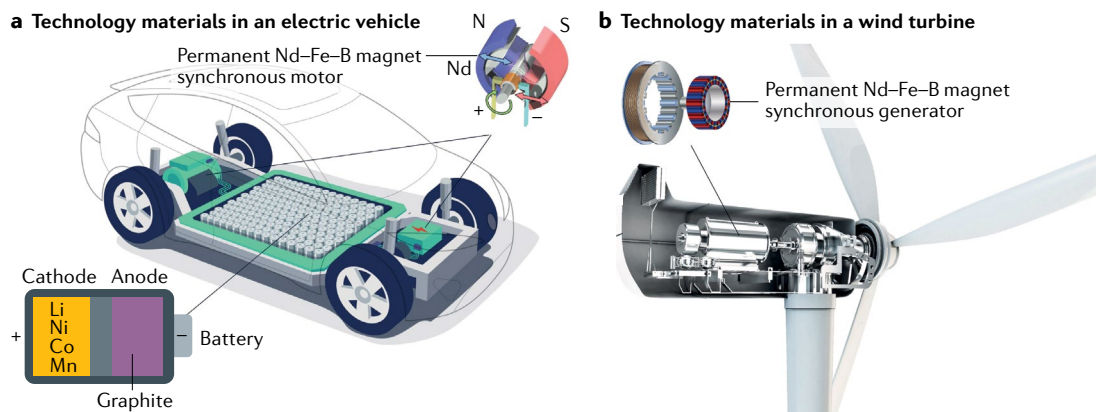


Fig. 1 | **Examples of low-carbon technologies that require transition materials.** **a** | Application of neodymium within a Nd–Fe–B magnet in electric vehicle direct drive motors. Lithium, nickel, cobalt and manganese are also used in the cathode of battery cells, and graphite is commonly used within the anode of electric vehicles<sup>16,173</sup>. **b** | Neodymium is also used within the permanent magnet synchronous generator in wind turbines. Electric car adapted from Peter Varga/Shutterstock.com. Motor (magnetic generator) adapted from Fouad A. Saad/Shutterstock.com. Turbine adapted from Andrea Crisante/Shutterstock.com.

can vary dramatically between battery manufacturers. Furthermore, the bill of materials of battery manufacturers continues to evolve as alternative battery chemistries are developed and deployed.

### Geological deposits

The same technology materials can be produced from a range of different types of ore deposits (FIG. 3) that have notably different direct and embodied environmental impacts<sup>12</sup>. For example, lithium hydroxide monohydrate can be produced from brine resources in the Lithium Triangle in South America or from hard-rock deposits in Australia. Each resource requires a different production process to extract and transform the natural resource into battery quality lithium hydroxide monohydrate. Even from the same resource, there are several ways to make the same final product<sup>34</sup>. This section gives a brief overview of the different types of technology material deposits. Furthermore, the reliance of some technologies on elements that are not mined on their own but, rather, recovered during the extraction (usually smelting) of other metals are discussed.

### Rare-earth elements

REE deposits have diverse geology<sup>21,35</sup> (FIG. 3). Most operating light REE (La, Ce, Nd, Pr) mines are in carbonate-related deposits, such as Bayan Obo and Maoniuping in China, Mountain Pass in the USA and Mount Weld in Australia. These are rare, carbonate-rich magmatic (sub-volcanic) rocks with enrichments of REEs that have often been further upgraded by hydrothermal fluids and/or weathering processes<sup>36</sup>. These deposits are straightforward to mine by routine open-pit methods, but their minerals can be intricately intergrown and challenging to upgrade. Alkaline igneous rocks (such as nepheline syenites) can have large, moderately high grade enrichments of REEs but are rarely mined, partly owing to their very complex mineralogy<sup>37,38</sup>. On the Kola Peninsula, Russia, loparite is produced from an underground mine in nepheline

syenite. Some REE deposits formed from hydrothermal fluids are also known but rarely mined, although the Browns Range deposits in Australia are at an advanced stage of exploration<sup>39</sup>.

REEs can also be produced from deposits formed by low-temperature processes such as weathering, erosion and sediment transport. In India, Madagascar and Australia, the REE ore mineral monazite is a by-product from mineral sand placer deposits, amenable to physical upgrading techniques that are cheaper and less chemical-intensive<sup>40,41</sup>. However, the mineral concentrates need to be dissolved (cracked), which requires acids. Also, concerns have been raised over radioactivity, owing to high Th contents in the monazite<sup>40</sup>.

The world's heavy REEs (for example, Dy, Tb, Y) are produced mainly from ion adsorption clays, in which the REEs are adsorbed onto clay surfaces<sup>42</sup>. Mining of ion adsorption clays has taken place in China for many years and has become more common in Myanmar<sup>43</sup>. Similar deposits are known in other countries such as Thailand<sup>44</sup> and Madagascar<sup>45</sup>. In situ or heap leaching is the preferred extraction method, as it removes the need for physical mineral processing or cracking.

The majority of REE mines extract mineral ores, which then need to undergo beneficiation and cracking<sup>46</sup>. The products of all of these mines then go to a chemical-intensive refining stage involving multiple stages of solvent extraction<sup>47</sup> to separate and purify the individual REEs to oxides and metals that are sold to the manufacturing supply chain. REE recovery is also possible by leaching bauxite as a stage in alumina production<sup>48</sup> and as a by-product of processing apatite for fertilizer phosphate.

### Lithium

Lithium resources can be categorized as brines, pegmatites and sediments<sup>49</sup> (FIG. 3). Brines are high total dissolved solids solutions of lithium, sodium, potassium and other salts. Most economic brine resources are found in high-elevation basins (salars) in South America, North America and Asia. However, they can

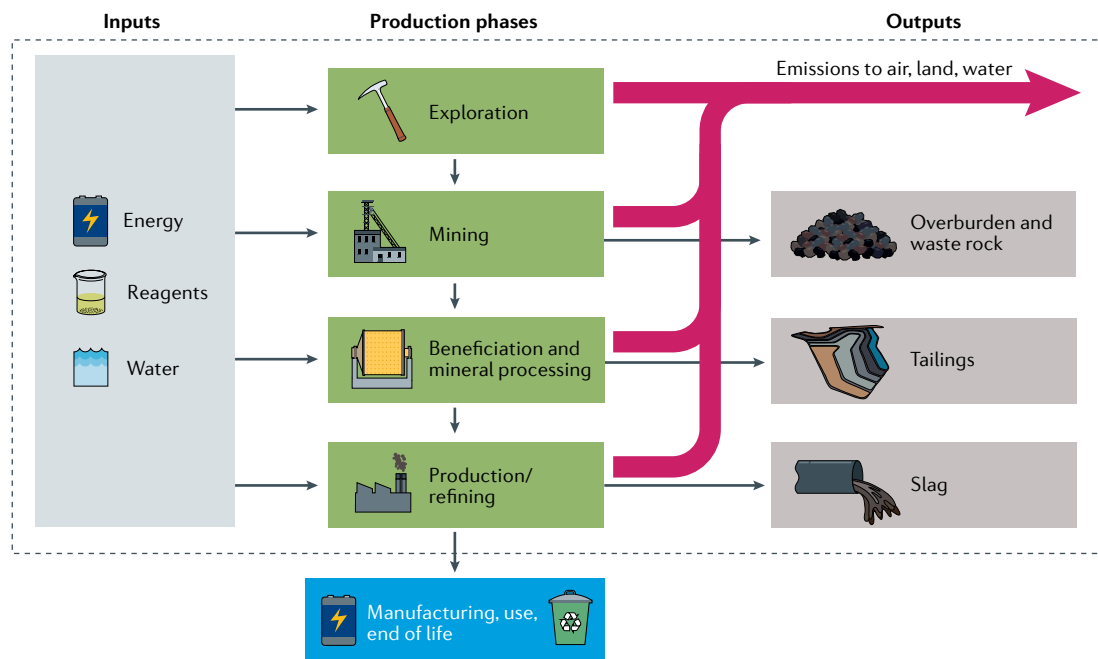


Fig. 2 | **The production phases for technology materials.** The flow diagram gives an overview of the inputs, production phases and outputs related to electric vehicle production. Emissions could include greenhouse gas emissions, pollutants and toxic substances<sup>174</sup>. Figure adapted with permission from REF.<sup>174</sup>, Elsevier.

also be found in deeper oilfields and geothermal brine fields worldwide. Brines from salars typically contain between 300 and 2,000  $\text{mg}_{\text{Li}} \text{L}^{-1}$ , whereas brines from oilfields and geothermal brine fields typically contain between 10 and 400  $\text{mg}_{\text{Li}} \text{L}^{-1}$ . Some of the most notable brine deposits in the world include Salar de Atacama (Chile), Salar del Hombre Muerto (Argentina), Clayton Valley (USA) and Salar de Uyuni (Bolivia)<sup>50</sup>.

Pegmatites are solid rock deposits, which contain natural lithium concentrations typically in the range 0.5–3%  $\text{Li}_2\text{O}$  by mass<sup>51</sup>. In pegmatites, lithium occurs in certain minerals, most commonly silicate or phosphate minerals (such as spodumene, lepidolite, zinnwaldite, amblygonite and petalite)<sup>51</sup>. These lithium-bearing minerals are associated with gangue minerals such as quartz and feldspar, as well as ore minerals for other commodities such as tantalum, caesium and tin<sup>52</sup>. Mineralized pegmatites take the form of sheet-like intrusions, typically tens to hundreds of metres thick and hundreds of metres to kilometres long. Some of the most notable pegmatite deposits in the world include the Greenbushes mine in Australia, the Tanco pegmatite in Canada and the Bikita pegmatite in Zimbabwe<sup>53</sup>.

Lithium deposits can also occur in sedimentary basins. Two main types of sedimentary lithium deposits include clays and borates. Lithium clay deposits, such as that at Thacker Pass in Nevada<sup>54</sup>, appear to form in clays that were originally deposited underwater (such as in lakes) and have been affected by later hydrothermal alteration. Lithium borate deposits occur in sediments deposited in lacustrine environments where evaporation of lithium-rich brines plays a part in the development of the sediments, along with hydrothermal alteration. The most notable known example of a lithium borate deposit is the Jadar deposit in Serbia<sup>55</sup>.

Brines can be processed in different ways as the lithium is dissolved in solution. During evaporative processing, the brine is pumped from underneath the ground and placed in large evaporation ponds, where the brine is exposed to sun and arid wind. Over 6–24 months, the water from the brine is evaporated, and the impurity salts are sequentially crystallized until a lithium concentrate is produced, typically  $\text{LiCl}$ , which can be further processed into lithium chemicals<sup>56</sup>. Direct lithium extraction removes lithium from the brine without the need to evaporate water or remove substantial quantities of impurities. A medium that contains a particular site (such as an adsorbent, ion exchanger or solvent) is used. Evaporation and direct lithium extraction processes can be combined in hybrid systems, such as the Fenix operation at the Salar del Hombre Muerto, Argentina<sup>57</sup>.

Lithium production from pegmatites and sediments is very different from the processing of brines<sup>58,59</sup>. First, the minerals are mined. Pegmatites require comminution to reduce particle sizes. Ore beneficiation processes such as froth flotation can be used to upgrade sediments to produce concentrates between 4% and 8%  $\text{Li}_2\text{O}$ . Mineral concentrates (such as spodumene) typically need to be treated at elevated temperatures to change the crystal phase to liberate lithium. In sedimentary deposits, roasting might not always be necessary. In both cases, the lithium is leached from the ore using chemicals. An aqueous lithium concentrate is produced that can be converted into lithium chemicals via chemical or (prospective) electrochemical processes, usually performed using sulfuric acid<sup>60</sup>.

### Cobalt

Cobalt production primarily originates from stratiform sediment-hosted copper deposits, magmatic nickel copper deposits or nickel laterite deposits<sup>61</sup>. Cobalt

**Class 1 nickel**

Refers to nickel products that have a nickel purity of a minimum of 99.8%.

mineralization also occurs in a range of other settings, including polymetallic veins and ferromanganese nodules and crusts on the seafloor (FIG. 3). Currently, primary cobalt production is always a by-product or co-product of nickel or copper production. The only exception is the ophiolite-hosted deposits of the Bou Azzer mine in Morocco<sup>62–65</sup>. Most cobalt mining globally occurs in the stratiform sediment-hosted deposits of the Central African Copperbelt<sup>66,67</sup>.

Battery quality cobalt sulfate can be produced from a chemical reaction between sulfuric acid and refined Co metal, or by refining cobalt hydroxides and oxides<sup>68</sup>. Sediment-hosted Cu–Co deposits contain oxidic or sulfidic ore, which both go through a comminution circuit following either open-pit or underground mining. Oxidic ore is leached. Cobalt is precipitated as a cobalt hydroxide intermediate product after having gone through several purification process steps. Sulfidic ore is concentrated through froth flotation, after which the concentrate is roasted, followed by a similar hydrometallurgical process as the oxide ore<sup>65,69</sup>.

Cobalt from laterite deposits is produced mostly by open-pit mining of limonite ore, followed by a hydrometallurgical high-pressure acid leach route to extract the metals of interest. Depending on specific process design, intermediate or final cobalt products come as Co sulfide, Co hydroxide, Co powder or Co metal<sup>65</sup>. Cobalt is produced as a by-product of nickel sulfide ore, which can be mined through both open-pit and underground mining methods. The ore is initially concentrated through froth flotation<sup>65</sup>, commonly followed by a pyrometallurgical process to produce a matte product in which the majority of the Co losses to the slag take place<sup>69</sup>. This matte product is then refined through a hydrometallurgical process to produce Co powder or Co metal<sup>65,69</sup>.

**Nickel**

Nickel sulfate is a common nickel product that is used in battery manufacturing, which is produced through a chemical reaction of sulfuric acid and class 1 nickel. Economic nickel resources are found in both hard-rock

deposits (magmatic-type and hydrothermal-type sulfide deposits) and laterite deposits formed by the weathering of nickel-rich protoliths (FIG. 3). Magmatic nickel sulfide deposits can form in a wide variety of geological settings and might be associated with vanadium, copper and platinum group element mineralization<sup>70</sup>. Nickel is also enriched in ferromanganese nodules and crusts occurring on the seafloor<sup>67</sup>.

Historically, the majority of nickel has been produced from magmatic sulfide ores due to the challenges in processing laterite ores<sup>23</sup>. Laterite ores can be divided into saprolite and limonite ores, of which only the limonite ores are suitable to produce nickel class 1 products through the hydrometallurgical high-pressure leaching process<sup>71</sup>. Specifically for nickel sulfide ore, the ore is mined through either open-pit or underground processes, and the ore is then crushed and ground and concentrated using froth flotation. The subsequent processing step is smelting of the concentrate into an intermediate product called matte, which can be refined into nickel class 1 using various techniques<sup>68,69</sup>. Nickel class 1 production from limonite ore comprises open-pit mining, screening, high-pressure and high-temperature acid leaching, neutralization and precipitation in the form of a sulfide or hydroxide intermediate product. This intermediate is refined through hydrogen reduction and electrowinning to produce nickel class 1 (REFS<sup>68,69</sup>). Alternatively, there is currently an industrial-scale bio-heap leaching process, consisting of open-pit mining, after which the ore is crushed and heap leached by acidic leaching solutions<sup>72</sup>.

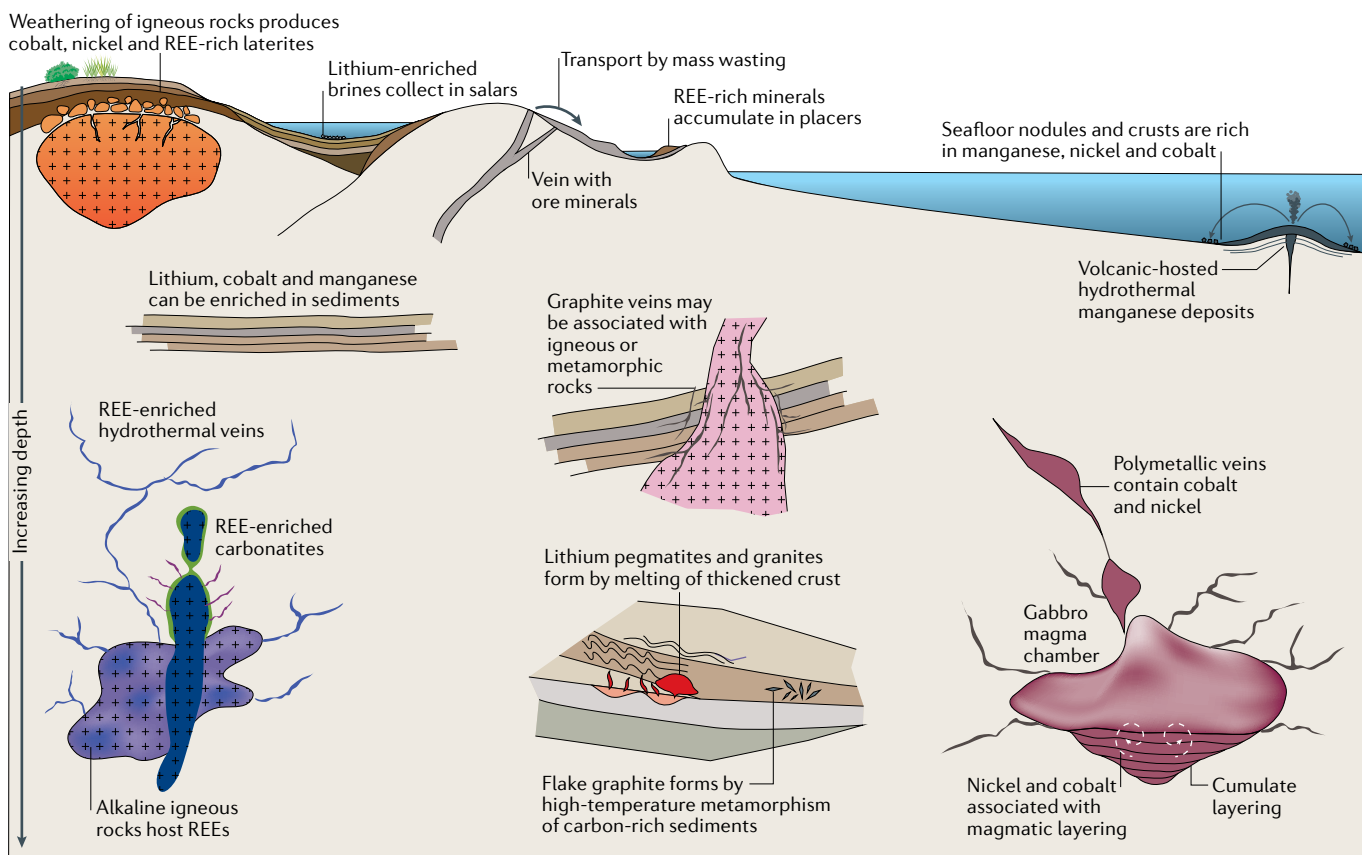
**Manganese**

Manganese has a range of ore minerals, dominantly manganese carbonates such as rhodochrosite and manganese oxides such as pyrolusite<sup>73</sup>. Land-based manganese resources occur most commonly as extensive layers of manganese-rich sedimentary rocks<sup>73</sup> (FIG. 3). These can be divided into manganese-rich sediments that occur independently of iron concentrations and manganese-rich sediments interlayered with ferruginous strata. The most important manganese deposits worldwide are

Table 1 | **Critical raw materials required in electric vehicle batteries, energy storage and direct drive motors**<sup>170–172</sup>

Element	Material	Purity requirements	Uses
Rare-earth elements	Neodymium (Nd), dysprosium (Dy)	99.95%+	Direct drive motor (permanent magnet)
Lithium	Lithium carbonate (Li <sub>2</sub> CO <sub>3</sub> ), lithium hydroxide monohydrate (LiOH·H <sub>2</sub> O)	99.5%+ Li <sub>2</sub> CO <sub>3</sub> in a lithium carbonate product and 56.5%+ LiOH in a lithium hydroxide product, both with impurities below specified levels	Battery cathode
Nickel	Nickel sulfate (NiSO <sub>4</sub> (H <sub>2</sub> O) <sub>6</sub> )	High purity	Battery cathode
Cobalt	Cobalt sulfate (CoSO <sub>4</sub> ·7H <sub>2</sub> O)	High purity	Battery cathode
Manganese	Manganese sulfate monohydrate (MnSO <sub>4</sub> ·H <sub>2</sub> O)	32% manganese content	Battery cathode
Graphite	Natural graphite, synthetic graphite	99.95% by weight, synthetic often higher purity, lower thermal expansion and better thermal stability	Battery anode
Vanadium	Vanadium pentoxide (V <sub>2</sub> O <sub>5</sub> )	High purity	Vanadium flow batteries





**Fig. 3 | Overview of the main geological deposit types for REEs, lithium, cobalt, nickel, graphite and manganese.** Weathered deposits, mineral sands and brines form at the land surface. Nodules and crusts form on the seafloor near mid-ocean ridges and hydrothermal vents. Sedimentary and volcanic-hosted deposits form in the shallow subsurface (for example, less than 4 km depth). Igneous and metamorphic deposits form ~>4 km below the surface. Diagrams are not to scale. REE, rare-earth element.

those of the Kalahari manganese field in South Africa, where manganese-rich sediments are interlayered with banded iron formations<sup>74</sup>. Manganese deposits can also be hosted in hydrothermally altered volcanic rocks. Furthermore, seafloor ferromanganese nodules and crusts are also important deposit types. Manganese can be concentrated by weathering and oxidation of manganese-rich source rocks into supergene-type deposits, such as those currently exploited in Gabon and Ghana.

Battery quality manganese sulfate can be produced through refining of electrolytic manganese metal or chemical refining of ore to produce lower-purity manganese sulfate<sup>75</sup>.

**Graphite**

Graphite can be produced from natural or synthetic sources<sup>76</sup>. Primary synthetic graphite derived from petroleum coke is used in the anode of most LIBs, owing to its relatively high purity, lower thermal expansion and better thermal stability<sup>77,78</sup>. Natural graphite can be classified into three types: amorphous graphite, vein graphite and disseminated flake graphite (FIG. 3). Only flake graphite is used in LIB applications<sup>76</sup>. Flake graphite is formed by the metamorphism of carbon-rich sediments and occurs in belts of metasedimentary rocks that have

been metamorphosed to high temperatures (amphibolite or granulite facies)<sup>79</sup>. Much of the world’s graphite is sourced from 170 mine areas across China<sup>80</sup>.

Natural graphite is mined by open-pit and underground methods, followed by beneficiation. To reach a 90–98% purity requires acid and/or alkali leaching of the gangue material to remove silicate and carbonate. To obtain a purity of 99.95% graphite for battery production, additional purification is required. Purification can be performed by hydrofluoric acid leaching, halogen or alkali roasting, and thermal treatment in an inert atmosphere<sup>76</sup>. Post-processing is required to produce the powder shape and sizes, which impart the surface properties needed for LIB anodes. This post-processing consists of milling, classification, shaping (spheroidization), coating to reduce surface area and packaging.

The production of synthetic graphite from petroleum requires green coke production followed by calcination and graphitization<sup>31,81</sup>. Green coke is produced as an intermediate product from oil refining that contains 5–15% volatiles. Removing the volatiles requires calcination or catalytic cracking of heavy oils<sup>82</sup>. The calcination phase produces needle coke, which has a purity of between 97% and 99%. Following calcination, the energy-intensive graphitization stage is where

calcined needle coke is conditioned and graphitized at about 2,500 °C in Acheson or Castner furnaces to produce high-purity graphite<sup>83,84</sup>. There is also research into developing more cost-effective and energy-efficient ways of synthetic graphite<sup>85</sup>.

### Vanadium

Vanadium occurs in a range of mineral deposit types. The most important are vanadiferous titanomagnetite deposits associated with layered mafic–ultramafic igneous intrusions and deposits hosted in sedimentary rocks, such as sandstone or shale. Weathering and oxidation of base-metal deposits can also lead to the formation of vanadate deposits. Currently, the majority of vanadium is produced as a co-product of iron and other metals from layered intrusions, such as the Bushveld Complex in South Africa. In addition to primary resources, a small proportion of global vanadium production is from waste, such as the residues of aluminium production from bauxite, hydrocarbon production residues and ash produced from burning coal.

### Environmental impacts

The environmental impacts associated with the production of technology materials can be substantial<sup>86</sup>. This section explores how LCA approaches can be applied to assess the environmental impacts of technology material production and discusses LCA studies conducted for REEs, lithium, cobalt, nickel, manganese and graphite.

### LCA

LCA is equally applicable to mining and refining technology materials as it is to the rest of the supply chain. LCAs can be used to quantify the environmental impact of services or products<sup>87</sup>, as well as being widely used for commercial, consumer and industrial products, including raw material and technology metals<sup>88,89</sup>. International standards such as ISO 14040 and ISO 14044 provide an overview of how LCA should be conducted, with further details being provided with documents such as the ILCD Handbook<sup>90</sup>.

The quantification of a product's life cycle greenhouse gas emissions, often referred to as a carbon footprint, represents one impact category, rather than the full suite of impact categories found in life cycle impact assessment (LCIA) categories<sup>91</sup>. The carbon footprint approach has gained traction in the last 10 years with the proliferation of corporate, project and product accounting and reporting methodologies<sup>92–94</sup>. Carbon footprints have been valuable for increasing consumer awareness and fostering discussions about the environmental impacts of products. However, it has been argued that this focus on a single impact category moves away from a fundamental motivation of LCA, which is to view a range of impacts in a holistic way to avoid problem-shifting by solving one environmental problem but creating a new one in the process<sup>95,96</sup>.

In the context of technology materials, LCA can be used in a variety of ways (FIG. 4). It is possible to evaluate the total environmental burdens and benefits of producing technology materials over the entire life cycle from cradle to grave. LCA includes production of the

raw materials, upstream impacts from consumables such as reagents or energy, transportation, reuse, recycling and end-of-life fate. A majority of LCA studies of original raw materials are 'cradle-to-gate', which means that the LCA incorporates the impacts of the production and manufacturing of the material from natural resources and not the impact associated with the downstream use of the materials. Others focus on a specific part of the value chain, such as a refinery. Alternatively, if LCA is focused on a single stage, it is referred to as a 'gate-to-gate' study.

The LCA approach to technology material production is particularly important because of the substantial amounts of energy and material inputs required to mine, process and refine to the required chemistry and purity, in addition to the associated emissions and waste outputs<sup>97</sup>. These impacts are included within LCA. The proportion of the product's upstream embodied impact outside a manufacturing company's direct operations can be substantial and provide opportunities for impact mitigation<sup>94,98</sup>.

**Rare-earth elements.** Cradle-to-gate LCA has been carried out for REE production from the largest producing mine, Bayan Obo, China. The carbon footprint results range from 22.8 to 35.1 kg CO<sub>2</sub> eq. per kg rare-earth oxide (REO)<sup>99</sup>. Prospective LCAs have been carried out for mixed REO production from carbonatites<sup>100</sup> and alkaline rocks<sup>101</sup>. LCAs have been carried out on ion adsorption deposits with carbon footprint results that ranged between 20.9 and 35.5 kg CO<sub>2</sub> eq. per kg REO assuming a 90–92% purity<sup>102</sup>, whilst another provided a range between 18.8 and 33.11 kg CO<sub>2</sub> eq. per kg REO with a 90% purity<sup>103</sup>. LCAs have also been carried out on separated REE production from monazite mineral sands with an average impact of 65.4 kg CO<sub>2</sub> eq. per kg for the 15 rare earths produced<sup>104</sup>. The LCA results range not just because the source of the material is distinct but also because the functional units vary, either at different stages in the REE production chain or with different proportions of individual REEs produced.

Gate-to-gate LCA has also been conducted on the solvent extraction phase of REE production with an impact of between 31.9 (REF.<sup>105</sup>) and 35.4 kg CO<sub>2</sub> (REF.<sup>106</sup>) eq. per kg Nd oxide, with a total impact from cradle-to-gate, which includes the mining, beneficiation, leaching and solvent extraction, being 105 kg CO<sub>2</sub> eq. per kg Nd (REF.<sup>106</sup>).

A range of other impact categories are important within the REE value chain, such as human and ecotoxicity for ion-adsorption-type deposits<sup>102</sup> and further development of impact categories is advised, especially to capture impact associated with radioactivity<sup>107</sup>.

**Lithium.** LCAs have been conducted on Li<sub>2</sub>CO<sub>3</sub> and, to a lesser extent, LiOH·H<sub>2</sub>O (REF.<sup>108</sup>). Li<sub>2</sub>CO<sub>3</sub> production from brine and spodumene sources has been compared. One study obtained operational data from a spodumene converter and the results indicated a carbon footprint of 15.8 kg CO<sub>2</sub> eq. per kg lithium carbonate equivalent (LCE)<sup>98</sup>, compared with 0.3 kg CO<sub>2</sub> eq. per kg LCE for the brine route<sup>109</sup>. Another study that examined future changes in impact based on resource and technology

Life cycle impact assessment (LCIA). A methodology for converting inventory data from a life cycle assessment into a set of potential impacts.

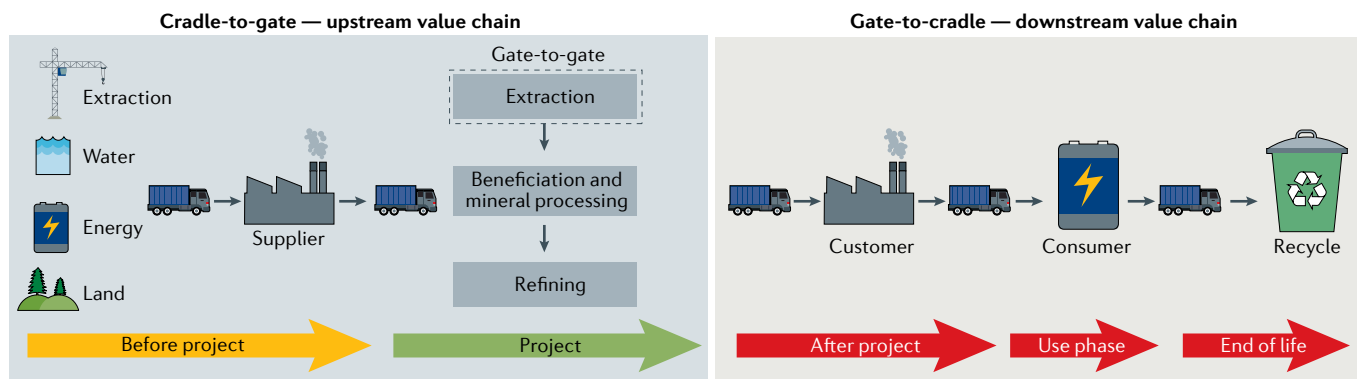


Fig. 4 | **Variations in life cycle assessment.** Different scopes of life cycle assessment highlight the distinction between the upstream and the downstream value chains from the perspective of a technology material producer. The distinctions between cradle-to-gate that would include the extraction of the raw material to the facility gate, gate-to-gate that would include one value-added process in the entire production chain and cradle-to-grave or cradle-to-cradle life cycle assessment that would consider all the environmental impacts associated with all the stages of a product's life.

change indicated that production from brine resources would see a carbon footprint increase from 3.2 kg CO<sub>2</sub> eq. per kg LCE in 2020 to 3.3 kg CO<sub>2</sub> eq. per kg LCE in 2100 (REF.<sup>34</sup>).

Water-related impacts are an important topic for lithium production. Brine water is in dynamic equilibrium with the environment and has a slow turnover controlled by evaporation and by recharge from the limited rains in the catchment<sup>110–113</sup>. Brine is not regulated the same way as freshwater in some jurisdictions, such as Chile<sup>114</sup>, but is regulated in the same way as freshwater in other jurisdictions, such as Nevada. The distinction in regulations has led to confusion in the industry over the question of whether brine should be considered as water or not. The impacts of lithium brine extraction on freshwater availability for ecosystems and humans can vary substantially between different operations, and the unique hydrogeology of the deposit determines how impacts will materialize.

**Cobalt.** According to the Cobalt Institute<sup>115</sup>, refined cobalt has, on average, a carbon footprint of 38 kg CO<sub>2</sub> per kg of refined cobalt and requires 883 MJ of primary energy. It must be noted that these values represent 30% of the global refined cobalt production and do not cover production in China<sup>65,116</sup>. Specifically, for an LCA carried out on a production route where refined Co is produced as a by-product of nickel, a carbon footprint of 11.7 kg CO<sub>2</sub> per kg was calculated<sup>89</sup>. To understand the life cycle impact of producing cobalt chemicals, the Argonne laboratory published the life cycle inventory (LCI) for Cu–Co mining from sedimentary copper–cobalt resources, producing an intermediate cobalt hydroxide product that is refined to battery quality cobalt sulfate heptahydrate in China<sup>117</sup>. However, this LCI for Cu–Co mining is adjusted assuming 80% Co recovery during processing, which is overestimated and does not account for variability due to deposit geology or processing route. An LCA study in 2020 showed that the carbon footprint for battery quality sulfate refined in Canada was half that for a refinery in China, namely, 1.6 compared with 3.3 kg CO<sub>2</sub> eq. per kg Co sulfate heptahydrate<sup>118</sup>.

Globally, from the cobalt by-product perspective, mine production is not always resource-efficient, as cobalt recovery rates and environmental footprint do not coincide for the various deposit types and processing routes. For instance, cobalt recovery rates from nickel laterites processed through hydrometallurgy are relatively high but the associated energy intensity is among the highest due to the necessity of heating during leaching. Comparatively, cobalt recovery from sediment-hosted copper–cobalt deposits is relatively low but much less energy-intensive. Specifically, the processing of deep sea manganese nodules to produce battery quality cobalt sulfate hex has been estimated to lead to a decrease of 30%, using economic allocation, for the cradle-to-gate carbon footprint, assuming 100% renewable energy use in the production process<sup>75</sup>. However, there is currently no production from these deposits.

**Nickel.** An industry average LCA has been carried out for battery quality nickel sulfate with 1 kg of nickel sulfate as the functional unit, representing 15% of the global production. On average, the study showed that the carbon footprint is 5.4 kg CO<sub>2</sub> eq. per kg Ni sulfate, with a primary energy demand of 84 MJ per kg Ni sulfate, of which only 5% of the consumed energy is renewable<sup>119</sup>. Specifically, for the production of nickel class 1, estimates have been made to quantify the difference in environmental impact of nickel class 1 being produced from sulfide or from laterite ore. All sulfide operations studied release less than 10 kg CO<sub>2</sub> eq. per kg metal, whereas for laterite projects, the annual release of greenhouse gases ranges from 25 to 46 kg CO<sub>2</sub> eq. per kg metal<sup>23</sup>, which aligns with other values reported for LCA studies covering high-pressure acid leach processing of nickel ore<sup>71</sup>. Specifically, the processing of deep sea manganese nodules to produce battery quality nickel sulfate has been estimated to lead to a decrease of 80%, using economic allocation, for a cradle-to-gate LCA, assuming 100% renewable energy use in the production process. There is currently no production from these deposits. For reference, the carbon footprint is 19.6 kg CO<sub>2</sub> eq. per kg Ni in nickel sulfate for terrestrial mining processes<sup>75</sup>.

Life cycle inventory (LCI). Inventory of input and output flows for a product system such as water, energy and raw materials, and releases to air, land and water.



**Manganese.** A cradle-to-gate LCA was carried out by the Global Manganese Institute<sup>120</sup>, with the functional unit as 1 kg of manganese alloy<sup>121</sup>. Studies have also been completed that form the Ecoinvent data set<sup>121</sup>. However, the Ecoinvent data set is not representative for high-purity manganese sulfate monohydrate going into the technology material value chain. The data provided in Ecoinvent are based on stoichiometric calculations and do not account for impurity removal, which is an important stage of the hydrometallurgical process. There is currently no industry-wide estimate of high-purity manganese sulfate monohydrate. For electrolytic manganese metal produced in China, an LCA study has been carried out<sup>75,122</sup>. Specifically, for the future processing of deep sea manganese nodules to produce battery quality high-purity manganese sulfate monohydrate, it was shown that this process could lead to a decrease of 22% for the cradle-to-gate carbon footprint, under economic allocation and assuming 100% renewable energy during the production process. For terrestrial-based resources, the carbon footprint was established at 6.4 kg CO<sub>2</sub> eq. per kg Mn in high-purity manganese sulfate monohydrate compared with 5.0 kg CO<sub>2</sub> eq. per kg Mn in high-purity manganese sulfate monohydrate for seabed resources<sup>75</sup>.

**Graphite.** LCIA data for graphite are limited. Previous academic work for anode grade graphite sourced from natural graphite deposits is estimated at 2.15 kg CO<sub>2</sub> eq. per kg (REF.<sup>109</sup>). A more comprehensive assessment of anode grade graphite production from natural flake graphite sources using a mixture of primary and secondary data indicated that the carbon footprint was 5.3 kg CO<sub>2</sub> eq. per kg (REF.<sup>123</sup>).

LCA was conducted on the graphitization stage of anode grade graphite from petroleum coke and coal tar pitch, resulting in a 4.9 kg CO<sub>2</sub> eq. per kg graphite<sup>16</sup>. This gate-to-gate study did not include impacts from upstream activities nor refining and calcination.

**Vanadium.** An LCA of a vanadium redox flow battery was conducted and is broken down into stages, which included the production of vanadium pentoxide (V<sub>2</sub>O<sub>5</sub>) sourced from titanomagnetite ore in South Africa<sup>124,125</sup>. In this LCA, the majority of the impact of vanadium redox flow batteries were embedded in the upstream processes. The climate change impact was 1.1 kg CO<sub>2</sub> eq. per kg vanadium pentoxide, which indicated that the grid mix for the region of production was coal-intensive<sup>124,125</sup>. Substantial reduction to this impact could be achieved in locations with renewable energy.

### Prospective LCA

LCA can be carried out during the operating phase and/or the development stages of a project<sup>126</sup>. One of the advantages of carrying out an LCA during the operating stage is that the foreground data quality will be improved, as there is the opportunity to directly measure data points such as reagent or energy consumption. However, a large proportion of mining impacts is determined by decisions made at the early development stages. Therefore, effective approaches to determine the potential environmental impacts of a technology

material early in development have much potential for mitigating impacts<sup>127</sup>. Prospective, or ex ante, LCA can be conducted during the development stages of projects whilst test work is being carried out and flow-sheets are being developed<sup>128</sup>. Environmental hotspots can be identified within a process and environmental impacts compared with current operating projects with equivalent functional units<sup>101,129</sup>. Advances have demonstrated opportunities for conducting LCA during the exploration phase<sup>130</sup>.

### Geometallurgy and integration with LCA

Geometallurgy initially started as a team-based approach combining geology and mineral processing to document variability within an orebody and quantify the impact of ore properties on process performance to produce 3D block models<sup>131</sup>. Nowadays, geometallurgy has evolved to a more multidisciplinary holistic approach, aiming at the best possible use of mineral raw materials in terms of energy and resource efficiency by integrating all relevant geoscientific disciplines with minerals and mining engineering<sup>132</sup>. It involves understanding and measuring geological, mineralogical and metallurgical ore properties to generate a database that can be integrated into a spatial predictive model for mineral processing design and operation, mine planning and financial analysis of future or existing mines<sup>132–134</sup>. The aims are to improve resource management, metallurgical process performance and, ultimately, the net present value of a mining project, while reducing operational and technical risks<sup>62</sup>. Beyond the above, geometallurgy can also be used to promote resource efficiency and reduce the socio-environmental impacts of all the extraction stages along the mining value chain<sup>62</sup>, for instance, by reducing acid consumption in hydrometallurgical circuits<sup>135</sup>, by increasing resource efficiency through the recovery of by-products from mine tailings and waste streams<sup>136</sup>, by improving tailings management and rehabilitation with regard to acid mine drainage<sup>137,138</sup>.

In practice, mineral-based geometallurgical approaches utilize quantitative information from two models, a 3D deposit model and a process model<sup>133</sup>. First, the deposit model documents the variability within the orebody. In particular, deposit models document properties that influence ore processing behaviour, such as ore grade (target metal grades), deleterious elements, ore mineralogy (minerals, texture) or any other relevant properties derived from geometallurgical testing, for example, comminution indexes, acid soluble metal content and acid consumption. Second, the process model uses the quantitative information from the geological model as input variables to forecast the metallurgical performance and define the mine plan over the lifespan of the operation through simulation. Typical simulation outputs include costs relating to capital expenditure (CAPEX) and operational expenditure (OPEX), recovery rates, throughputs, energy, and water and reagent consumption per tonne of ore.

It seems surprising that, despite these synergies between geometallurgy and LCA, there has not been a call for an integration of these two methods. Indeed, while geometallurgy is becoming standard practice

#### Geometallurgy

Combining geology or geostatistics with metallurgy (or, more specifically, extractive metallurgy) to create a spatially or geologically based predictive model for mineral processing plants.

#### CAPEX

Capital expenditures (CAPEX) that are major purchases a company makes, designed to be used in the long term.

#### OPEX

Operating expenses (OPEX) refer to day-to-day expenses that are incurred during business activities.

at the early stage of mining projects, applications of LCA evaluation have been historically decoupled from mine planning or process design and remain mainly limited to retrospective environmental assessments of already operating mines<sup>139</sup>. Incorporating LCA to geometallurgy at the early stages of a mining project would allow inclusion of environmental factors during the evaluation of different scenarios, resulting in integrated decision-making that maximizes process and environmental performance.

Joint optimization of the performance and environmental impact of mining operations can be achieved through the proposed integrated LCA–geometallurgical approach (FIG. 5). In principle, going beyond the traditional approaches by integrating LCA within geometallurgy (and vice versa) at the early stage of a mining project could deliver many benefits. First, it allows the design of energy-efficient and resource-efficient processes at the feasibility stage, such that the ore geometallurgical variability can be managed to deliver a product respecting the fixed specifications, while minimizing the carbon footprint. This approach also allows for a more holistic definition of the orebody boundaries (project resources and reserves) not only based on grade but also on economic and environmental assessment of the whole mine value chain from ore to product.

Another benefit is the ability to plan the production schedule to ensure the most efficient use of the resources at all stages of extraction, from a technical, environmental as well as social perspective. This proactive management could also result in planning more effectively the mine closure, as well as remediation and rehabilitation strategies, based on quantitative geometallurgical information, therefore, ensuring long-term environmental impact mitigation and improving social acceptance<sup>62</sup>. With this improved geometallurgical understanding of the mineral resources, it would then be possible to identify potential by-products or co-products and develop suitable, profitable processes for the co-production of materials to maximize resource efficiency. The combined approach could also lead to strategies for waste minimization and better management of potential deleterious elements or problematic minerals<sup>64</sup>, notably, by predicting their behaviour during processing to recover these or reduce their content in tailings<sup>140,141</sup>. An additional benefit of such an approach is the possibility to support traceability and responsible sourcing along the mine value chain, by providing information and quantitative data on the various material flows (from ore to product) that could help real-time transparency of the chain of custody (from source to consumer)<sup>63</sup>.

Process simulation is a critical enabling technology, allowing a geometallurgy approach beyond the traditional LCA based on economic indicators and system boundaries, offering a more holistic process improvement based on orebody knowledge. Additional software tools exist to translate simulation outputs (mass and energy) to LCA/environmental impact indicators such, as global warming potential and acidification potential, to name a few<sup>142</sup>. For instance, the use of process simulation combined with LCA has been successfully applied to compare different flowsheet scenarios for primary

copper production<sup>143,144</sup>, evaluate the environmental impact of refractory gold processing<sup>145,146</sup> or choose a suitable energy source for an REE processing plant<sup>100</sup>. Environmental impact indicators thus generated based on spatially explicit data could be used to produce an environmental block model of the deposit. This block model, along with the economic block model, could then be used to support mine planning and scheduling over the life of mine. The potential benefit of such an approach has been illustrated in the case of iron ore mining, although limited to ore extraction and not including the processing stages, by using a carbon footprint block model to constrain long-term mine scheduling simulations, therefore, allowing for minimization of the project CO<sub>2</sub> emissions while maximizing its economic performance<sup>147</sup>.

So far, only a limited number of studies have included ore geometallurgy variability in their LCIA. An attempt at incorporating ore variability in LCA has been proposed for the Bear Lodge REE project (USA) through a temporally explicit LCA<sup>101</sup>. This analysis highlighted that differences in ore compositions resulting from variation in ore mineralogy might substantially change the carbon footprint over the life of mine.

Overall, the proposed integrated approach provides the means for a simultaneous quantification and optimization of the environmental impacts (through LCA), processes and/or economics (through geometallurgy) of mining projects, based on in situ ore properties and simulation. Therefore, these approaches allow for a more accurate and dynamic optimization of raw materials extraction resource efficiency.

### Minimizing environmental impacts

Various approaches can be adopted to limit environmental impacts when producing technology materials. Life cycle impacts such as carbon footprint, land use impact or water impacts of technology material extraction and processing can be mitigated in several ways. First, efforts should be made to understand and research environmental impact mitigation potential for deposits that exhibit fundamental and unavoidable environmental impacts.

### Impact mitigation opportunities

Processing can be electrified wherever possible, allowing for renewable energies such as solar and wind to be incorporated with minimal technology innovation required<sup>148</sup>. In this way, as the grid reduces carbon intensity via these new energy sources, the carbon intensity of technology material production will decrease. The processing routes can also explore additional opportunities to reuse or recycle energy and material streams within the process<sup>143,149</sup>. Reagents can be purchased from suppliers who implement similar strategies as technology material manufacturers<sup>150</sup>. For example, sodium carbonate used in lithium processing can be produced from natural trona ore deposits<sup>151</sup> or through the Solvay process<sup>152</sup>. Each production pathway and specific supplier can have notably different impacts per kilogram of equivalent material produced<sup>153</sup>. Technology material manufacturers should identify which pathways deliver the

lowest global warming potential products and purchase reagents from those suppliers.

It is common for mining and metal projects to generate co-products<sup>154</sup>. These can be industrial minerals, metals or energy. In LCA, co-products can represent opportunities to offset costs and environmental impacts.

Notably, several critical raw materials, including vanadium and REEs, can be produced as by-products from alumina production. However, such generation of by-products is not always viewed favourably because it increases costs, despite having potential environmental benefits. Careful techno-economic analysis of

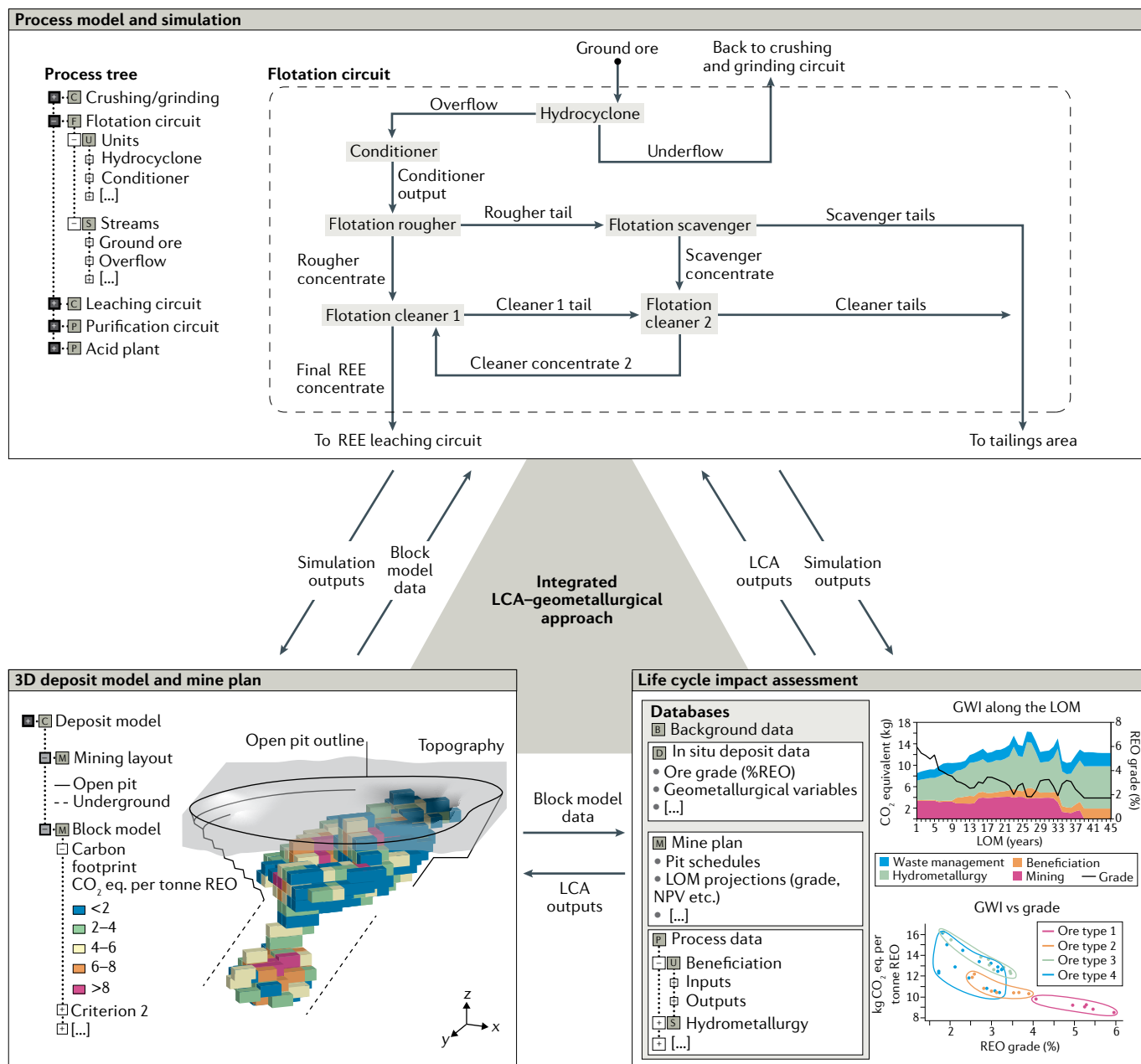


Fig. 5 | **Integrated LCA-geometallurgical approach.** For a joint optimization of the economic performance and environmental impact of mining operations, the life cycle assessment (LCA)-geometallurgical approach relies on three components and/or models that provide quantitative data to each other: the 3D deposit model and mine plan, the process model and the LCA model. In the 3D deposit model (block model within an open-pit mine), each block is assigned attributes, such as: grades, density, geometallurgical variables (for example, hardness, comminution indices, acid consumption) or environmental impact criteria (for example, carbon footprint, particles emissions), among others. These attributes can be used for data management, mine planning and scheduling, forecasting production and testing different scenarios. The

process model is composed of units (for example, ball mill, flotation cells) and streams (for example, concentrate, tailings, process water), and used to design and simulate process outputs and forecast production. The LCA model is used to evaluate the environmental impact of each stage of the overall operation, such as the carbon footprint<sup>100</sup>, based on simulation and/or process data and in situ ore properties. LCA models allow the examination of different project options (such as energy source, acid regeneration, water recycling). NPV, net present value; REE, rare-earth element; REO, rare-earth oxide. The flotation circuit in the 'process model' was created with HSC Chemistry software ([www.outotec.com](http://www.outotec.com)) and adapted. The plot of global warming impact (GWI) along the life of mine (LOM) was adapted from REF.<sup>101</sup>, CC BY 4.0.

these processes is required. Another example of a type of project in development that could deliver substantial decarbonization opportunities is geothermal lithium. In these projects, lithium is extracted from deep, hot geothermal brines to produce lithium chemicals and low-carbon electricity. This electricity can often have lower impacts relative to the grid of the country. For example, Germany's grid is still a high CO<sub>2</sub> intensity grid with heavy coal use. The offsetting credit from producing low-carbon power and displacing coal on the German grid can incur a substantial carbon offset credit for a geothermal lithium product.

#### **Circular economy thinking**

Products containing technology materials are expected to grow substantially, and recycling these products could become a notable source of these materials when they reach the end of their life. Appropriate circular economy strategies such as reuse, remanufacturing and recycling can reduce the reliance on virgin materials<sup>155</sup> and potentially help meet demand entirely in the next few decades<sup>156</sup>. However, some suggest that recycling products such as LIBs and hard disk drives do not necessarily provide environmental benefits, depending on a range of factors, such as the material recovery rate and processing technologies<sup>157,158</sup>. Therefore, more research is still needed to better understand the environmental performance of technology materials produced from secondary sources compared with primary sources. There are also opportunities for circular economy approaches at mine or mineral processing sites, whereby economic materials are extracted from mine tailings and waste streams<sup>159</sup>.

#### **Opportunity for carbon sequestration**

There are opportunities for certain mineralogies and projects related to technology metals, notably, nickel with cobalt as a by-product, to sequester carbon dioxide<sup>160</sup>. 40 Gt of CO<sub>2</sub> is released each year into the atmosphere from anthropogenic and natural sources<sup>161</sup>. Approximately 50% of this CO<sub>2</sub> contributes to global warming, whereas the other half is consumed by the ocean and terrestrial biosphere<sup>162</sup>. A diverse portfolio of renewable energy generation technologies and methods for reducing greenhouse gas concentrations in the atmosphere is required to prevent global temperatures rising above the average warming of 2 °C by 2100 (REF.<sup>162</sup>), including negative emission approaches such as carbon mineralization<sup>162–164</sup>.

These negative emission approaches involve reactions between CO<sub>2</sub>, magnesium-rich and calcium-rich silicate rocks such as mantle peridotites, basaltic lavas or ultramafic intrusions to produce inert carbonate minerals such as magnesite or limestone (MgCO<sub>3</sub> and CaCO<sub>3</sub>, respectively)<sup>165</sup>. These reactions occur naturally, albeit over slow geological timescales<sup>165</sup>. The prime reactive minerals in these rock types are brucite (Mg(OH)<sub>2</sub>) and olivine ((Mg, Fe)<sub>2</sub>SiO<sub>4</sub>), which react relatively quickly, sequestering 0.76 and 0.62 tonnes of CO<sub>2</sub> per tonne of materials, respectively<sup>165</sup>. Other more common minerals have the potential to capture substantial amounts of CO<sub>2</sub>, however, the carbonation reaction is considerably

slower<sup>165</sup>. Therefore, systems need to be engineered to increase mineral dissolution rates via grinding to produce more fresh reactive surface areas, or possible biological approaches, such as the Mount Keith Nickel Mine, Western Australia, that draw bivalent cations into solution, stabilizing dissolved HCO<sub>3</sub><sup>–</sup> and, eventually, producing carbonate minerals<sup>165</sup>. The operating Mount Keith Nickel Mine sequesters 39,800 tonnes per year of atmospheric CO<sub>2</sub>, offsetting the mine's annual greenhouse gas emissions by 11%<sup>166</sup>.

The maximum sequestration potential of carbon mineralization by these rock types is up to ~60,000,000 Gt CO<sub>2</sub>, if the resource is fully carbonated and if these approaches were economically viable<sup>162</sup>. The Dumont Nickel Project is a prime example of passive carbon mineralization, with 21,000 kg CO<sub>2</sub> per year being sequestered through mine tailings, offsetting the annual carbon emissions of the mine operation by up to 16%<sup>167</sup>. If engineered or biological methods can accelerate the dissolution of other minerals to release cations such as Mg and Ca in mine wastes, and massive natural outcrops of suitable geology, such as ophiolite complexes, these have the potential to sequester 10<sup>5</sup>–10<sup>8</sup> Gt CO<sub>2</sub> (REFS<sup>162,163</sup>). Although there are still numerous challenges, modelling and experiments have shown the potential for carbon mineralization as a long term and relatively cost-effective negative emission technology<sup>162</sup>.

#### **Summary and future perspectives**

Mineral demand for use in EVs and battery storage will be growing at a rapid pace until 2040. Lithium will see demand growth by over 40 times, graphite, cobalt and nickel by 20–25 times and REEs demand to triple by 2040 in a sustainable development scenario modelled by the International Energy Agency<sup>168</sup>. To meet the demand for technology materials, several new mines, mineral processing plants and refineries will need to be developed<sup>169</sup>. The opportunity exists now, at the beginning of marked demand increase, to identify projects that have environmentally favourable conditions and support those projects that progress to quantify and minimize environmental impacts by utilizing integrated LCAs and integrated geometallurgy approaches.

Understanding environmental performance well in advance can help developers, investors, regulators, technology material buyers and other off-takers make decisions early on, before impacts are incurred, as, after impacts have been incurred, it is often too late to make changes to mitigate those impacts. Future research should focus on supporting early environmental impact assessments by linking geologists and LCA practitioners with mining and mineral processing engineers to develop integrated frameworks for sustainable resource development.

At the early stages of assessing and exploring REEs, lithium, nickel, cobalt, manganese, graphite and vanadium deposits, geologists can consider a range of factors that could relate to the potential environmental impact of mining and downstream processing. For example, it is possible to identify potential co-production of more than one technology metal from a mine. It is also possible to maximize resource efficiency and assess the ore



deposit's grade and 3D structure, which affects how much land will be impacted during mining. The geometallurgy of the ore determines how it will behave during processing, with implications for resource efficiency, consumption of energy and water, materials and the resulting waste.

The electric revolution and decarbonization agenda will see global society shift from a fossil-fuel-based economy to a mineral-based one. The negative social and environmental impacts of mining these materials have drawn attention as production ramps up to meet the increased demand<sup>63</sup>. A focus on end-to-end raw material traceability and linking LCA performance data, along with good quality social and governance data within the supply chains, is an important step to ensure that raw materials feeding the transition have minimal impact.

Research should focus on this integration and provide case studies for best practice.

Environmental impacts of production can be high, therefore, achieving sustainability for technology materials production is a real challenge that needs to be tackled through broader, more systematic and holistic use of LCA during the initial exploration, mining and refining stages and incorporation with approaches such as geometallurgy. It is only through the application of integrated and predictive approaches all along the value chain — such as the combined LCA–geometallurgy approach suggested here — that society will reach a low-carbon economy with technologies that are genuinely sustainable from cradle-to-grave.

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#### Author contributions

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The authors declare no competing interests.

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