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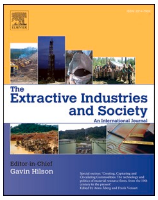

Review article

A comparative review of material supply chains and sustainability pathways in steel and battery technologies

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ABSTRACT

Global material sourcing is undergoing an unprecedented transformation, particularly in the critical steel and battery sectors, which underpin infrastructure, mobility, and the global clean energy transition. Driven by a complex interplay of geopolitical tensions, climate imperatives, technological innovation, and market volatility, the sourcing of raw materials has become a focal point of industrial strategy and policy debate. This review explores the structural shifts and strategic responses shaping material supply chains in the 21st century. China's industrial rise, the decline of traditional producers, and the systemic vulnerabilities of lean global supply chains are analyses through empirical and theoretical lenses. The paper evaluates the adoption of decarbonisation technologies such as Electric Arc Furnaces (EAF) and hydrogen-based steelmaking, as well as the evolving chemistry and circular economy potential in lithium-ion battery production. In doing so, it highlights the risks posed by Critical Raw Material (CRM) dependencies, ethical supply concerns, and the uneven global policy landscape. Digital innovations and life cycle assessment frameworks are presented as enabling tools for transparency and sustainability. Ultimately, this review argues for a reorientation of global sourcing strategies centred on resilience, circularity, and governance to achieve climate targets and equitable industrial growth.

1. Introduction

Global material sourcing is increasingly recognised as a critical issue at the intersection of economic growth, sustainability, and geopolitical security. The demand for raw materials such as steel, lithium, cobalt, nickel, and graphite has surged in recent decades, fuelled by infrastructure expansion, the digital revolution, and the global push towards electrification and climate neutrality. This intensifying demand has coincided with numerous external shocks, including the 2008 global financial crisis, the COVID-19 pandemic, and the 2022 energy crisis, exposing the fragility of the world's complex, interdependent supply chains.

The industrial sectors most sensitive to these supply dynamics are steel and batteries. Steel remains foundational to infrastructure, construction, and manufacturing, while batteries are central to the clean energy transition, particularly in electric vehicles (EVs) and renewable energy storage systems. However, both sectors face mounting challenges in securing reliable, ethical, and environmentally sustainable access to critical raw materials. Traditional sourcing strategies that prioritised cost-efficiency and globalised logistics are increasingly seen as insufficient in an era defined by climate change, resource nationalism, and supply chain disruption.

This review aims to integrate and extend the analysis of these challenges by examining the material sourcing dynamics of the steel and battery industries.

By taking a comparative approach, the paper seeks to highlight not only the sector-specific issues but also the broader systemic transformations needed to ensure secure and sustainable material sourcing in the 21st century.

2. Shifting geopolitical and industrial dynamics

China's commanding role in global steel production, accounting for 54 % of total global output in 2023 ("World Steel in Figures 2024," 2025)exemplifies the broader industrial transformation driven by Newly Industrialised Countries (NICS). A combination of state-directed industrial policy, significant infrastructure investment, and cost-efficient manufacturing models has underpinned this ascendancy (Pinto and Diemer, 2020) In contrast, More Economically Developed Countries (MEDCS) have increasingly pivoted away from large-scale production

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toward specialised, high-value, and lower-volume manufacturing. (Matykowski and Tobolska, 2021) interpret this transition as part of a structural reconfiguration of global economic hierarchies. However, (Richardson-Barlow et al., 2022) caution that such high-value strategies remain vulnerable due to their dependence on complex, globally distributed supply chains, many of which are heavily reliant on critical raw materials (CRMS). Tables 1 and 2 shows the evolution of global steel production from 2003 to 2023, highlighting China's dramatic 363 % increase in output, juxtaposed against the relative stagnation or decline of traditional producers such as the United States, Japan, and Germany.

Recent shocks, including the 2008 financial collapse, 2015 commodities slump, and the COVID-19 pandemic, have revealed the systemic fragility of global supply networks. In addition (Laing, 2020) noted that COVID-19 had severe short-term impacts on mining, disrupting operations and livelihoods, underscoring how pandemic lockdowns and global demand shocks exposed the fragility of mineral supply chains. Furthermore (Giese, 2022) highlighted that competition for critical raw materials (like lithium, cobalt) increased through policy shifts such as resource nationalism, stockpiling, which emerged amid pandemic disruptions. (Ripsman, 2021) details how the UK's supply chains are particularly susceptible to these disruptions, a point echoed by (Venger and Shumska, 2021), who argue that the UK's industrial strategy lacks the foresight necessary to pre-empt such systemic risks. In contrast, nations with more proactive industrial strategies, like South Korea or Germany, have demonstrated greater resilience by integrating long-term vision with agile response mechanisms.

Protectionist responses have re-emerged, often under the guise of resilience-building. (Tan et al., 2019) criticise of lean supply chains for lacking shock-absorbing capacity, whereas (Pellegrino et al., 2024) promote supplier diversification as a counterstrategy. Johnson and Haug (2021) argue that they isolate domestic producers and curtail participation in efficient global networks.

Amidst this evolving industrial landscape, green industrial policies have emerged as strategic efforts to align economic growth with environmental sustainability. Initiatives such as the United Kingdom's Clean Steel Fund and the European Union's Emissions Trading System exemplify this approach. However, authors such as (TC Davis, 2024) and (Javid, 2016) argue that these frameworks remain fragmented, often lacking cohesion and cross-sectoral integration. Comparative assessments reveal notable asymmetries: while the EU demonstrates regulatory comprehensiveness, China's environmental strategies are usually constrained by limited transparency, and Japan's reliance on voluntary mechanisms poses risks of underperformance (Smyer Yü, 2024). This policy unevenness hinders coordinated climate action, particularly across complex, transnational value chains where regulatory misalignment can amplify systemic inefficiencies.

A more granular comparison between the United Kingdom and Ukraine, as presented in Tables 3 and 4, illustrates the steep decline in both countries' steel production volumes and international rankings over the past two decades. Ukraine fell from 7th to 24th place globally, while the United Kingdom declined from 17th to 26th. This trajectory highlights the vulnerability of regional producers amid global industrial realignment and the overconcentration of production capacity in East Asia. Furthermore, the data underscores chronic underinvestment in domestic steelmaking infrastructure, particularly in post-Soviet and Western European economies, exposing structural weaknesses that limit their competitiveness in a rapidly evolving global market (INTERNATIONAL IRON AND STEEL INSTITUTE, 2004; "World Steel in Figures 2024," 2025).

Table 1
The comparison of the national output, market share, and output growth for the top 10 crude steel producers in 2003 (INTERNATIONAL IRON AND STEEL INSTITUTE, 2004; "World Steel in Figures 2024," 2025).

Global Position	Country (2003)	Tonnage (2003)	Market Share (2003)
1	China	220.1	23 %
2	Japan	110.5	11 %
3	USA	90.4	9 %
4	Russia	62.7	6 %
5	S. Korea	46.3	5 %
6	Germany	44.8	5 %
7	Ukraine	36.9	4 %
8	India	31.8	3 %
9	Brazil	31.1	3 %
10	Italy	26.7	3 %

Table 2
The comparison of the national output, market share, and output growth for the top 10 crude steel producers in 2023 (INTERNATIONAL IRON AND STEEL INSTITUTE, 2004; "World Steel in Figures 2024," 2025).

Global Position	Country (2023)	Tonnage (2023)	Market Share (2023)	Change
1	China	1019.1	54 %	363 %
2	India	140.8	7 %	27 %
3	Japan	87.0	5 %	−21 %
4	USA	81.4	4 %	−10 %
5	Russia	76.0	4 %	21 %
6	S. Korea	66.7	4 %	44 %
7	Germany	35.4	2 %	−21 %
8	Türkiye	33.7	2 %	84 %
9	Brazil	31.8	2 %	2 %
10	Iran	31.0	2 %	292 %

Table 3
The comparison of the national output, market share, and output growth for the United Kingdom and Ukraine in 2003 (INTERNATIONAL IRON AND STEEL INSTITUTE, 2004; "World Steel in Figures 2024," 2025).

Country	Global Position (2003)	Tonnage (2003)	Market Share (2003)
Ukraine	7	36.9	3.82 %
UK	17	13.3	1.38 %
World		964.8	

Table 4
The comparison of the national output, market share, and output growth for the United Kingdom and Ukraine in 2023 (INTERNATIONAL IRON AND STEEL INSTITUTE, 2004; "World Steel in Figures 2024," 2025).

Country	Global position (2023)	Tonnage (2023)	Market share (2023)	Change in tonnage
Ukraine	24	6.2	0.3 %	−83 %
UK	26	5.6	0.2 %	−58 %
World		1892.2		96 %

3. The fragility of lean global supply chains

Protectionist trade measures are increasingly employed as reactive buffers against global supply chain volatility, though their outcomes are often ambiguous. (Tan et al., 2019) argue that, despite their efficiency, lean supply chains lack the built-in redundancy required to absorb shocks. In contrast, (Johnson and Haug 2021) advocate for diversification across both geographies and suppliers as a foundational strategy for resilience. The United Kingdom's post-Brexit imposition of 25 % tariffs on steel imports exemplifies a nationalist shift in trade policy. While the UK Trade Remedies Authority justifies these tariffs as protective measures for the domestic industry, (Johnson and Haug 2021) caution that such actions may entrench inefficiencies and further isolate UK firms from established international trade networks.

A complex interplay of technical capabilities and socio-political dynamics shapes resilience in global material supply chains. (Pires Ribeiro and Barbosa-Povoa, 2018) define resilience as the capacity of a supply chain to prepare for, respond to, and recover from disturbances while maintaining acceptable levels of cost and service. (Selepe and Makinde, 2024) quantify the economic implications, estimating that supply disruptions contribute to >50 % of operational costs. Nevertheless, internal organisational barriers remain significant. For example, (Cadden et al., 2022) identify resistance to enterprise resource planning (ERP) systems and limited digital literacy as key impediments to resilience-enhancing initiatives.

Four interdependent characteristics underpin resilient supply chains: flexibility, redundancy, velocity, and visibility (Pires Ribeiro and Barbosa-Povoa, 2018). Flexibility refers to the capacity for rapid adaptation to market volatility and is often achieved through supplier diversification and agile procurement strategies (Pellegrino et al., 2024; Piprani et al., 2022; Wiendahl et al., 2024). In material sourcing, this may entail reducing single-supplier dependencies or reallocating orders dynamically in response to geopolitical shifts and trade risks.

Redundancy, typically achieved through safety stocks, multiple sourcing options, and contingency planning, acts as insurance against supply disruptions. However, it often conflicts with the cost-minimisation ethos of lean manufacturing (Tan et al., 2019; Zavala-Alcívar et al., 2020), underscoring the strategic trade-offs between efficiency and robustness in global sourcing frameworks.

Velocity and visibility, the speed of information flow and the traceability of products across the supply chain are greatly enhanced through digital integration, particularly ERP systems (Cadden et al., 2022; Kirmizi and Kocaoglu, 2022). Yet, digital transformation remains uneven due to resistance to technological change and interoperability challenges (Selepe and Makinde, 2024). In increasingly complex and risk-prone material supply environments, these two capabilities are critical not only for operational resilience but also for supporting ethical sourcing by improving transparency into material origins and processing practices.

The steel industry exemplifies both the complexity and the possibility of systemic reform. Approaches such as closed-loop sourcing, secondary scrap integration, and reverse logistics offer the potential to enhance material efficiency and significantly reduce emissions. (Nechifor et al., 2020) emphasise the logistical and environmental benefits of such strategies, particularly in reducing emissions from primary resource extraction and transport. However, (Richardson-Barlow et al., 2022) caution that increased reliance on scrap streams introduces challenges related to quality control, material degradation, and contamination. This divergence reflects a broader tension within decarbonisation efforts, balancing ambitious environmental targets with the operational feasibility and quality demands of industrial production.

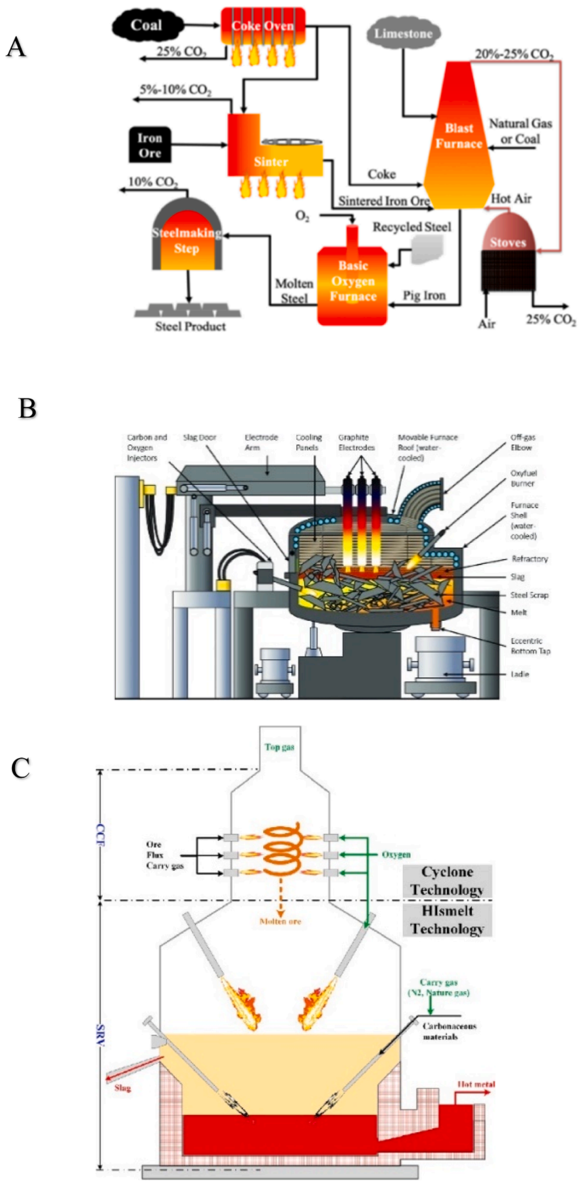

Fig. 1. (A) A blast furnace-basic oxygen furnace system, reproduced from (Rouch, 2023) (B) An electric arc furnace system, reproduced from (Hay et al., 2021)(C) HIsarna® system reproduced from (Htet et al., 2021).

4. Decarbonisation pathways in the steel industry

Decarbonisation remains a central concern for the steel industry, which is responsible for approximately 7–9 % of global carbon dioxide emissions. Traditional blast furnace-basic oxygen furnace (BF-BOF) systems, shown in Fig. 1A are inherently carbon-intensive due to their reliance on coal as both an energy source and a reducing agent. In response, several technological pathways have emerged—most notably Electric Arc Furnaces (EAF), depicted in Fig. 1B, Hydrogen-based Direct Reduction (H2-DRI), and the HIsarna® process (Fig. 1C). Molten Oxide Electrolysis (MOE) is another emerging route aimed at producing iron via direct electrolysis of iron ore without CO₂ emissions (Wei et al., 2019) While EAFs offer immediate emissions reductions by using electricity to melt scrap steel or directly reduced iron (DRI), H2-DRI has the potential to fundamentally transform ironmaking by replacing coke with green hydrogen. HIsarna®, an alternative smelting reduction technology, also promises efficiency gains but remains heavily dependent on carbon capture, utilisation, and storage (CCUS) systems (Chen et al., 2023; Wang et al., 2023). Furthermore, as many steel producers plan to transition from traditional blast furnace ironmaking to Hot Briquetted Iron (HBI) production, a deeper examination of emerging smelting-based technologies is required. These include smelting reduction processes capable of producing liquid or solid iron feedstocks without coke, offering a transitional pathway between BF-BOF and hydrogen-based direct reduction systems. Although promising, these approaches remain at pilot scale and face technical challenges, including high energy intensity, reactor material degradation, and dependence on renewable-based power inputs (Ariyama, 2025). Unlike a conventional blast furnace, smelting-reduction processes like HIsarna eliminate the need for coke ovens and sinter plants by directly smelting iron ore, allowing the use of lower-grade ore; however, they still rely on coal-based reductants and remain highly energy-intensive. Around 18 GJ per tonne of steel, meaning that without CCUS their CO₂ footprint remains substantial (Vogl et al., 2018). Practical limitations temper the promise of these technologies. (Gao et al., 2021) highlight that while decarbonised production pathways can substantially reduce emissions, they often require costly infrastructure overhauls, face feedstock limitations, and depend on broader energy system transformation. For instance (Shahabuddin et al., 2023) highlighted that replacing blast furnaces with direct reduction processes to produce Hot Briquetted Iron

(HBI) demands new ironmaking methods. Smelting reduction technologies (e.g., HIsarna) or high-temperature hydrogen-based smelting concepts offer transitional pathways by producing liquid iron with limited or no coal use, though these remain at the pilot stage.

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For instance, (Shahabuddin et al., 2023) highlighted that replacing blast furnaces with direct reduction processes to produce Hot Briquetted Iron (HBI) demands new ironmaking methods. Smelting reduction technologies (e.g., HIsarna) or high-temperature hydrogen-based smelting concepts offer transitional pathways by producing liquid iron with limited or no coal use, though these remain at the pilot stage. The case of EAF adoption illustrates these regional disparities. In the United States, over 70 % of steel production now occurs via EAFs, driven by low electricity prices and abundant scrap availability. Conversely, the United Kingdom lags at just 19 %, constrained by high energy costs and a carbon-intensive electricity grid. Table 5 compares EAF adoption rates across the UK, EU, and USA, alongside electricity pricing and energy source composition. These discrepancies suggest that policy support, energy pricing structures, and grid decarbonisation are critical enablers of technological transitions.

Hydrogen-based steelmaking is another promising decarbonisation pathway. The H2-DRI process involves the direct reduction of iron ore using hydrogen, eliminating the need for coke. However, this approach depends on the large-scale availability of green hydrogen, which itself is energy-intensive to produce via electrolysis. Technological underpinnings, such as partial oxidation, steam reforming, and the water-gas shift reaction, underpin industrial hydrogen production (Eqs. (1)–3).

$$C_nH_{2n+2} + \frac{n}{2}O_2 \rightarrow nCO + 2nH_2 (+\ heat) \tag{1}$$

Eq. (1)**: General formula for the partial oxidation of hydrocarbons** (Boretti and Banik, 2021).

$$C_nH_{2n+2} +\ nH_2O\ (+heat) \rightarrow nCO + (2_n + 1)H_2 \tag{2}$$

Eq. (2)**: General formula for steam reforming of a hydrocarbon** (García, 2015)

$$CO +\ H_2O \rightarrow CO_2 + H_2\ (+\ heat) \tag{3}$$

Eq. (3)**: Water-gas shift reaction** (Boretti and Banik, 2021)

Yet, without abundant renewable electricity and electrolyser infrastructure, the process remains economically and logistically constrained. (Hassan et al., 2023) and (Wang et al., 2023) acknowledge hydrogen's transformative potential, but caution that current capacities are insufficient to support wide-scale deployment.

CCUS technologies also feature prominently in decarbonisation scenarios, particularly for retrofitting existing BF-BOF systems. (Pandey et al., 2022) endorse post-combustion capture for its retrofit compatibility, but others, such as (Míguez et al., 2020) and (Silva et al., 2020) question its economic viability due to high operational costs and long-term storage risks. (Wilberforce et al., 2019) explore innovative pathways such as CO_2-to-fuel conversion, though these remain at pre-commercial stages. These debates reflect a recurring theme: technological readiness does not guarantee economic or infrastructural feasibility.

Table 5
A comparison of national EAF adoption to electricity price and sources ("Electricity Prices Around the World, 2021; Energy Institute Statistical Review of World Energy, 2023; Makeuk, 2005; Nechifor et al., 2020).

Country	EAF Adoption (%)	Electricity Price ($/kWh)	Coal (%)	Gas (%)	RES (%)
EU	39	0.241	15	20	37
UK	19	0.448	2	38	40
USA	67	0.172	20	40	16

In response to these challenges, governments are increasingly adopting green industrial policy frameworks to facilitate low-carbon transitions. In the UK, instruments such as the Clean Steel Fund, Industrial Energy Transformation Fund, Climate Change Levy (CCL), and participation in the Emissions Trading Scheme (ETS) aim to drive emissions reductions. However, (TC Davis, 2024) and (Javid, 2016) argue that the policy environment remains fragmented, lacking both horizontal integration across sectors and vertical alignment between policy levels. Internationally, the regulatory landscape is similarly uneven: while the EU's ETS is considered comprehensive, China's carbon trading mechanisms remain opaque, and Japan's voluntary commitments suffer from weak enforcement mechanisms. Table 6 outlines key UK decarbonisation policies.

Renewable energy integration into mining and manufacturing also offers short- to medium-term decarbonisation potential. Solar thermal, biomass combined heat and power (CHP), and geothermal systems can reduce reliance on fossil fuels. However, (Pouresmaieli et al., 2023) note that current renewable energy systems struggle to meet the high temperature demands of steelmaking. Concentrated solar power and bio-based fuels are promising but remain limited in scale and geographic applicability. Decentralised steel production in regions with abundant renewables may offer niche advantages, contributing to both energy security and material resilience.

While the steel industry exemplifies the complexities of decarbonising heavy industrial sectors, similar challenges arise in other strategically vital domains most notably battery manufacturing. As the global shift toward electrification and renewable energy accelerates, batteries have become essential enablers of the low-carbon transition. However, their production is deeply embedded in vulnerable and resource-intensive supply chains. The following section examines the structure of battery supply chains and their critical dependencies on specific raw materials, highlighting the geopolitical, environmental, and economic risks that must be addressed to ensure long-term sustainability and security.

5. Battery supply chains and CRM dependencies

Modern battery manufacturing is fundamentally reliant on critical raw materials (CRMs) such as lithium, cobalt, nickel, and manganese, particularly in the production of high-performance lithium-ion batteries for electric vehicles (EVs) and renewable energy storage systems. These elements are indispensable due to their unique electrochemical properties, which contribute to enhanced energy density, thermal stability, and battery longevity (Blomgren, 2017). Cobalt, for example, plays a crucial role in stabilising cathode materials and improving thermal resilience (Larcher and Tarascon, 2015). However, the geographic concentration of CRM reserves presents considerable vulnerabilities for global battery supply chains. (Ali et al., 2023)highlight the strategic

Table 6
Energy efficiency policies implemented in the UK (Bailey and De Propris, 2014; Giampieri et al., 2019).

Government policies	Key points
Climate Change Levy (CCL)	Taxes energy sources (electricity, gas, coal, LPG) for non-domestic sectors to encourage reduced energy consumption.
Climate Change Agreement (CCA)	Offers financial incentives for carbon-intensive industries to improve energy efficiency or reduce carbon footprint.
EU Emissions Trading Scheme (ETS)	Limits GHG emissions and allows carbon allowance trading, promoting efficiency in manufacturing.
Carbon Reduction Commitment (CRC)	Targets non-energy-intensive sectors not covered by CCA or EU-ETS based on energy consumption.
Energy Saving Opportunity Scheme (ESOS)	Evaluates energy use and identifies cost-effective efficiency improvements for industries.

risks associated with this dependency, particularly in relation to geopolitical instability and market volatility.

The extraction of CRMs is also associated with significant environmental and ethical challenges. Mining operations, especially for cobalt and nickel, are linked to deforestation, water contamination, and elevated greenhouse gas emissions. The Democratic Republic of the Congo (DRC), which supplies over 60 % of the world's cobalt, has faced widespread scrutiny for exploitative labour practices, including child labour and unsafe working conditions (Nemery and Banza Lubaba Nkulu, 2018). These issues underscore the urgent need for more ethically responsible and environmentally sustainable sourcing strategies. For example (Sändig et al., 2024) demonstrated that mining projects in Guinea and the DRC often concede to local community and pressures when faced with sustained protests, especially if host governments and international activists apply pressure.

In response to these concerns, significant research efforts have been devoted to developing alternative battery chemistries. Iron- and manganese-based cathodes are under investigation as less environmentally harmful substitutes, though they typically have lower energy densities. Similarly, sodium-ion batteries replacing lithium with the more abundant sodium have shown promise in stationary energy storage applications yet continue to face performance limitations in terms of cycle life and stability (Vaalma et al., 2018). Despite their environmental appeal, CRM-free or CRM-reduced technologies remain constrained by technological and economic barriers. (Thackeray et al., 2012) argue that these alternatives are not yet commercially competitive due to immature supply chains, underdeveloped manufacturing ecosystems, and lower electrochemical performance. Moreover, retrofitting existing infrastructure to accommodate new materials would require substantial capital investment and introduce further logistical complexity.

A sustainable pathway for battery manufacturing is likely to involve a multi-pronged strategy encompassing material substitution, advanced recycling technologies, and improved material efficiency. Hydrometallurgical processes and direct cathode recycling are emerging as viable methods for recovering valuable materials and reducing dependence on virgin CRMs (Dunn et al., 2012). Complementary policy mechanisms such as extended producer responsibility (EPR) schemes, targeted subsidies, and strategic stockpiling will be critical in facilitating industrial transitions and de-risking supply chains (Gaines, 2014).

(Mayyas et al., 2023) argue that improving recycling rates and transitioning toward less resource-intensive cathode chemistries, particularly those that reduce cobalt content, can enhance long-term supply security for lithium-ion batteries, noting that the global battery recycling market is projected to grow to roughly $24 billion by 2030 and could help alleviate raw material shortages. This is further discussed by (Nuur et al., 2026), identifying structural tensions such as institutional inertia and path dependency while outlining technological innovations, new business models, and shifts in production routines as pathways for transformative change across micro, *meso*, and macro levels. Meanwhile, (Eadson et al., 2023) contend that decarbonising foundational industries such as steel and mining requires not only technological advances but also socially inclusive transition strategies that acknowledge the geographically uneven impacts on workers and communities. Together, these studies underscore how circular strategy, innovation in battery chemistry, systemic reform in extractive practices, and place-based just transition policies can collectively support supply chain resilience, sustainability, and industrial decarbonization.

The strategic importance of batteries to the global energy transition further amplifies the fragility associated with concentrated CRM supply. Many of these materials, including cobalt, lithium, and graphite, are sourced from politically unstable or environmentally sensitive regions. Security-oriented analyses by (Gaustad et al., 2017) emphasise the risks of overreliance on such jurisdictions, especially amid geopolitical disruption. (Di Noi et al., 2020)caution against overestimating the immediate potential of recycling and substitution technologies, arguing that innovation alone cannot fully compensate for the deeper geopolitical asymmetries embedded in current supply chains.

This dilemma is particularly acute in the rare-earth element (REE) sector, where the lack of functional substitutes heightens strategic vulnerability. (Silvestri et al., 2021) call for urgent policy intervention and coordinated diversification to address the supply insecurity of REEs. By contrast, (Zhang et al., 2021) adopt a more optimistic view, citing recent advancements in substitution research and early-stage diversification efforts. These contrasting perspectives reflect a broader uncertainty surrounding the scalability and long-term viability of alternative sourcing models.

(Jovine and Paz, 2025) examines lithium extraction in the "Lithium Triangle" (Bolivia, Argentina, Chile), highlighting tensions between foreign investment and resource nationalism, and questioning whether current practices risk reproducing historical patterns of dependency and exploitation in the Global South. In addition (Agusdinata and Liu, 2023) analyses global news coverage from 2015 to 2021, revealing heightened concern over social and environmental impacts, including indigenous rights, resource access, community benefits, governance, and supply shortages for minerals such as cobalt, graphite, copper, and manganese. Together, these works emphasise the need for sustainable sourcing strategies, international coordination, and stronger governance frameworks to mitigate socio-environmental risks and prevent extractive dynamics from echoing past injustices as demand for EV battery minerals accelerates. These themes are reinforced by (Sovacool, 2019) which documents both the socio-economic benefits and the severe harms associated with cobalt mining in the Democratic Republic of Congo (DRC), and provides nuanced policy recommendations. In a later article (Sovacool, 2021) further exposes widespread child and forced labour, sexual exploitation, and "modern slavery" in artisanal Congolese cobalt mining, emphasising exploitation by local elites and traders and calling for urgent reforms. In addition (Liu and Agusdinata, 2021) uses an agent-based model to show how lithium brine extraction in Chile's Salar de Atacama depletes groundwater, creating acute water stress and long-term social disruption for indigenous communities. Collectively, these studies highlight that as demand for EV battery minerals accelerates, international coordination, robust governance, sustainable water management, and humanitarian safeguards are required to prevent past extractive injustices from re-emerging across the Global South.

The challenges of critical raw material dependency, ethical sourcing, and supply chain fragility underscore the need for a more regenerative, resource-efficient approach to industrial production. Within this context, the circular economy offers a transformative framework that moves beyond linear models of extraction, use, and disposal. By prioritising resource recovery, product life extension, and closed-loop material flows, circular strategies can mitigate CRM-related risks, reduce environmental impacts, and enhance long-term resilience in battery and broader manufacturing systems.

6. Circular economy and life cycle assessment

Circular economy models, as shown in Fig. 2, offer a promising framework. Circular economy (CE) models provide a theoretical framework for sustainable production by keeping resources in use and minimising waste. For example, Lieder and Rashid's framework organises circular strategies hierarchically, highlighting loops for reuse, remanufacturing, and recycling (Lieder and Rashid, 2016). As shown by (Viles et al., 2022) and (Kaniappan Chinnathai and Alkan, 2023) these models gain practical strength when coupled with Industry 4.0 technologies (the suite of digital innovations like Internet of Things, digital twins, and additive manufacturing). Emerging Industry 4.0 tools can indeed improve productivity and deliver smarter processes that reduce environmental impacts. They enable closed-loop systems, for instance, IoT sensors and connectivity help firms track products through their life cycle and recover materials, supporting CE's goal of "closing the loop (Pigosso et al., 2022). As mentioned by (O'Connor, 2025). additive

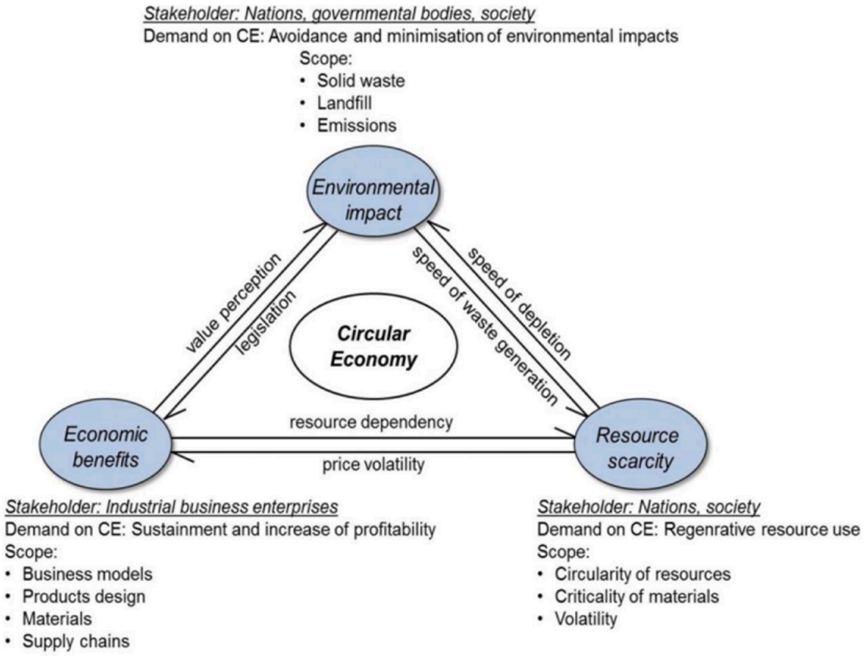

Fig. 2. Circular economy framework reproduced from (Lieder and Rashid, 2016).

manufacturing (3D printing) also contributes by reducing material waste and enabling on-demand production, aligning with circular principles of minimal waste and localised production.

However, researchers caution that technology is not a neutral fix for sustainability challenges. (Kaniappan Chinnathai and Alkan, 2023) and (Sajadieh and Noh, 2025) noted in proposing a digital lifecycle framework for energy-intensive industries, note that simply deploying IoT or AI without systemic changes might overlook social and environmental nuances. In fact, unchecked digitalisation can exacerbate issues like high energy consumption or ethical concerns. (Lopes de Sousa Jabbour et al., 2018) highlighted that early enthusiasm about Industry 4.0′s benefits has sometimes led to premature conclusions. The relationship between I4.0 and CE is complex, and realising true sustainability requires careful integration of technology, business models, and stakeholder behaviour.

Life Cycle Assessment (LCA) provides a critical methodology for mapping environmental impact and supports process redesign by identifying emissions hotspots (Zikulnig et al., 2025). (Piron et al., 2024) showed that LCA can reveal that the manufacturing phase of a product accounts for the majority of its carbon footprint, signalling an opportunity for process redesign or material substitution. This hotspot analysis guides engineers and managers to focus on the improvements that yield the greatest environmental benefits.

The integration of Life Cycle Inventory (LCI) data enhances benchmarking (Piron et al., 2024) while system expansion allows impact allocation across co-products like slag (Suer et al., 2022) and (Üçtuğ et al., 2025) promote cradle-to-grave models as more holistic, though industry uptake often favours cradle-to-gate models for pragmatic reasons. A key strength of LCA is its ability to pinpoint life-cycle stages that are particularly resource-intensive or polluting.

System boundaries and LCA scope are important considerations. While academics often promote cradle-to-grave assessments (covering a product's entire life cycle from raw material "cradle" to disposal "grave") as the most comprehensive approach, many industries opt for cradle-to-gate models that end at the factory gate (product delivery) for practical reasons. Cradle-to-grave LCAs are more holistic; they capture all stages and thus provide a complete environmental footprint. This broader scope helps avoid burden-shifting; improvements in one stage won't inadvertently cause worse impacts in an unassessed stage. (Üçtuğ et al., 2025) argued that cradle-to-grave models better align with circular economy thinking by considering use and end-of-life phases. However, cradle-to-gate studies remain popular in industry because they require less data and focus on the portions of the life cycle a manufacturer can directly control. In practice, both approaches have value: cradle-to-gate LCAs can drive incremental improvements within production, while cradle-to-grave LCAs can inform more systemic changes and innovation to improve a product's entire life cycle.

Another methodological aspect is handling co-products and byproducts in processes. LCA provides techniques like system expansion to allocate environmental impacts fairly when a process yields multiple valuable outputs. For example, (Suer et al., 2022) highlighted that in steelmaking, blast furnace slag is a co-product that can replace cement in construction. Instead of arbitrarily assigning some fraction of the steel mill's emissions to slag, system expansion credits the slag for avoiding impacts from producing an equivalent amount of cement.

Bridging the gap between theoretical sustainability frameworks and real-world practice is increasingly possible by linking LCA with Industry 4.0 systems and corporate sustainability metrics. One emerging trend is the integration of LCA-based measures into companies' Environmental, Social, Governance (ESG) reporting and decision-making processes. Life Cycle Sustainability Assessment (LCSA), an extension of LCA that includes social and economic impacts, can map onto ESG criteria. By aligning ESG metrics with recognised LCA standards, organisations create a unified and transparent assessment framework. In fact, (Padilla-Rivera et al., 2024) introduce a framework where LCA indicators feed into ESG disclosures, improving consistency in how companies report climate and environmental performance. Such integration enhances transparency and accountability: stakeholders can see ESG reports grounded in rigorous life-cycle data rather than surface-level statistics. It also helps in identifying discrepancies – for example, if a firm's ESG report claims low carbon footprint but an LCA reveals high upstream emissions, that gap becomes evident and can be addressed. Introduce a framework that integrates LCA indicators into ESG disclosures, improving consistency in how companies report their climate and environmental performance. Such integration enhances transparency and accountability: stakeholders can see ESG reports grounded in rigorous life-cycle data rather than surface-level statistics. It also helps identify discrepancies. For example, if a firm's ESG report claims a low carbon footprint but an LCA reveals high upstream emissions, that gap becomes evident and can be addressed.

Industry 4.0 technologies are key enablers in this integration. Modern digital systems provide the data streams and connectivity needed to perform LCA continuously or dynamically. A recent review enumerated four digital technologies with significant potential for enhancing LCA: IoT, big data analytics, artificial intelligence (AI), and blockchain (Popowicz et al., 2024). IoT sensors embedded in equipment and products can automatically collect data on energy usage, material consumption, and emissions during production and even during product use. This real-time data can feed into dynamic LCAs or digital dashboards, allowing companies to monitor sustainability performance as closely as they monitor production efficiency (Piron et al., 2024). Digital twins take this a step further by simulating processes they enabling dynamic LCA, where one can model how changes in a process might reduce environmental impacts before implementing them in reality (Petri et al., 2025; Sajadieh and Noh, 2025).

Other Industry 4.0 tools address data quality and trustworthiness in sustainability accounting. Blockchain technology can provide an immutable ledger for recording environmental data and product provenance, particularly in complex supply chains. By linking blockchain-verified supply chain data with LCA models, companies ensure greater credibility in their emissions reporting and ESG claims (Popowicz et al., 2024). Meanwhile, AI and big data analytics can process the massive amounts of information from IoT and other sources to identify patterns and anomalies, for instance, AI algorithms can analyse energy consumption across multiple plants to flag unusually high usage that merits investigation.

The benefits of integrating LCA with digital systems include improved accuracy, timeliness, and stakeholder trust, but challenges persist. One issue is that data from different sources may have inconsistent formats or quality. Ensuring data standards and compatibility is crucial, a point underlined by (Newman and Styring, 2022) who call for greater standardisation and institutional support for LCA as it evolves into a broader sustainability tool. Indeed, despite advances, inconsistencies in methodological scope and reporting standards today undermine LCA's potential as a universal yardstick. Authors such as (Wunderlich et al., 2021; Zimmermann et al., 2020) have been calling for harmonised methods so that LCA-based assessments are comparable across industries and regions.

Policy remains a determining factor. As discussed by (Kuneman et al., 2023) EU policy initiatives have spurred circular practices by coupling regulatory targets with market incentives. The EU ETS, for instance, has provided measurable prompts for low-carbon innovation in industry, though its overall impact on technological change remains moderate; achieving long-term climate and circularity goals will require tightening and refining this policy mechanism. (Chen et al., 2024) highlighted that life-cycle assessment is increasingly embedded in EU policymaking to guide waste and product regulations, yet aligning traditional LCA methods with forward-looking, 10–20 year policy scenarios poses challenges; recent analyses of EU waste policy note that such prospective policy applications of LCA face methodological gaps that still need to be addressed.

(Okullo et al., 2023) showed that China has substantially broadened its circular economy policy framework in the past decade, deploying both command-and-control measures and market-based instruments. A national carbon emissions trading scheme has generally incentivised cleaner production and innovation in key industries, although studies suggest these ETS-driven gains are modest and that more stringent implementation is needed to meet China's climate targets. However, it has been discussed by (Bleischwitz et al., 2022) despite numerous circular economy initiatives and high-level plans, China faces serious difficulties in translating pilot successes into wider adoption: many local circular projects fail to scale up sustainably, and policy coordination gaps between regions and sectors persist, undermining the enforcement and effectiveness of circular economy strategies

(Liu and JIN, 2025)highlighted that Japan was an early adopter of circular economy principles nd is now integrating carbon-market tools to drive further change. Under the 2020s Green Transformation (GX) strategy, Japan launched a voluntary corporate emissions trading system in 2023, with plans to transition it into a nationwide mandatory ETS by fiscal year 2026 and to introduce a new carbon levy on fossil fuels by 2028.

In the UK, a domestic emissions trading scheme was established in 2021 to maintain carbon-pricing incentives for industry, but overall progress in the circular economy has been uneven. Key sectors still encounter practical and policy barriers to circularity. For example (Ferriz-Papi et al., 2025) highlighted that the construction industry, responsible for a major share of UK waste, reports recycling or recovering over 90 % of its construction and demolition waste, yet this is largely achieved via low-value downcycling and a pervasive "blame culture" endures in which many stakeholders view such waste as inevitable and costly rather than preventable. These conditions highlight the UK's implementation gap: insufficient supporting legislation, limited investment in recycling infrastructure, and weak market demand for secondary materials are cited as primary challenges hindering the broader adoption of circular economy practices nationwide.

7. Conclusions

The sustainability and security of global material sourcing are now central concerns for industrial strategy and environmental governance. This review has highlighted the increasingly precarious balance between economic efficiency, geopolitical stability, and ecological responsibility within the steel and battery sectors,two foundational industries driving infrastructure development and the clean energy transition. The reliance on globally concentrated, high-risk supply chains for critical raw materials such as lithium, cobalt, and nickel has exposed structural vulnerabilities, particularly during periods of crisis and disruption.

In the steel sector, decarbonisation efforts are advancing through a range of technological pathways, including Electric Arc Furnaces, hydrogen-based direct reduction, and CCUS integration, but these innovations face practical, financial, and infrastructural constraints. Disparities in energy policy, electricity pricing, and industrial support mechanisms create uneven transitions across regions, limiting the global scalability of low-carbon solutions. Similarly, battery manufacturing is heavily reliant on materials sourced from environmentally sensitive and politically unstable regions, complicating ethical and sustainable sourcing goals. Despite progress in alternative chemistries and recycling technologies, most substitutes are not yet commercially or technologically mature.

The circular economy and Life Cycle Assessment (LCA) frameworks offer promising pathways to improve material efficiency, reduce waste, and enhance supply chain resilience. However, the successful integration of these approaches depends on addressing current gaps in digital infrastructure, standardisation, and policy coherence. Industry 4.0 technologies and stronger ESG alignment can enable more transparent, accountable, and adaptive systems, yet must be supported by consistent regulatory frameworks and international collaboration.

Ultimately, securing a sustainable future for material sourcing will require a paradigm shift from linear, cost-driven extraction models to more regenerative, circular systems that prioritise resilience, ethics, and environmental stewardship. This will involve not only technological innovation but also strategic foresight, cross-sectoral coordination, and bold policy interventions. As global demand for critical materials intensifies, the imperative is clear: the time for fragmented, reactive measures has passed. A coherent, forward-looking strategy is essential to build robust material economies capable of supporting both industrial growth and planetary boundaries in the decades to come.

CRediT authorship contribution statement

Liam O'Connor: Writing – original draft, Writing – review & editing.

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