ICMM Mining with Principles

From Mine to Grid

Aligning Mining and Energy Systems for the Clean Energy Transition

Table 1. List of Abbreviations

Abbreviation	Definition
BEV	Battery electric vehicle
CapEx	Capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CEO	Chief Executive Officer
EaaS	Energy-as-a-Service
EDF	Électricité de France (EDF)
ESG	Environmental, social and governance
ETS	Emissions Trading System
EU	European Union
EU ETS	European Union Emissions Trading System
EV	Electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
GW	Gigawatt
HEV	Hybrid electric vehicle
ICMM	International Council on Mining and Metals
IEA	International Energy Agency

Abbreviation	Definition
IFC	International Finance Corporation
IMF	International Monetary Fund
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Energy
LOM	Life of Mine
MW	Megawatt
NDC	Nationally Determined Contribution
NEF	New Energy Finance (referenced in the report as Bloomberg NEF/NEF)
OEM	Original Equipment Manufacturer
OpEx	Operating expenditure
PPA	Power Purchase Agreement
PPP	Public Private Partnership
R&D	Research and development
ROI	Return on investment
TCO	Total cost of ownership
TWh	Terawatt-hour

Contents

Executive Summary

01

Climate change is an unprecedented global challenge – its impacts are systemic, cross-border and affect us all. Rising global temperatures are intensifying extreme weather events, disrupting natural ecosystems, placing food production and water supply under growing strain, damaging critical infrastructure and contributing to climate-driven displacement and migration.

Achieving vital international climate targets – such as tripling renewable energy capacity by 2030 and reaching net zero emissions by 2050 – will require around 3bn tonnes of critical minerals. While the focus must be on scaling metal and mineral recycling, this alone will not allow the industry to meet 100% of demand. For example, it is estimated that by 2030, 300 new mines will be needed to deliver the materials the world needs.[1]

The traditional perspective on this challenge has been one of 'constraint', defined by overwhelming demand for critical minerals and the seemingly inescapable energy and carbon intensity of mining operations. However, a shift in perspective is needed; one that recognises decarbonisation not only as an operational necessity but as a strategic investment opportunity. This shift positions mining as both the driver and the beneficiary of catalytic innovation and highlights the role of mining not only in reducing its own emissions, but in enabling wider system-level decarbonisation. As large, energy-intensive operations, mine sites can act as anchor demand for renewable energy, support the development of shared infrastructure, and catalyse investment in low-carbon energy systems that extend beyond the mine gate. Reframing decarbonisation in this way highlights its potential to create value, drive innovation across the value chain and contribute to more resilient and integrated energy systems.

Findings from the International Council on Mining and Metals (ICMM)'s recent *Global Mining & Metals Greenhouse Gas (GHG) Emissions Dataset* show that total Scope 1 and 2 emissions from the sector accounted for 11% of global emissions in 2024 (with 3% of emissions from mining and 8% from metal processing).[2]
This positions the sector as the sixth-largest source of global GHG emissions, just behind sectors such as power generation, transport and agriculture.

While the emissions footprint of mining operations themselves may appear relatively small in global terms, at 3%, it presents a significant and often under-recognised opportunity at the local and regional level. Targeted reductions in Scope 1 (direct on-site) and 2 (indirect from purchased electricity) emissions offer a clear and actionable pathway for mining operators to contribute meaningfully to global climate goals, as well as local sustainable, economic and industrial development goals, while investing in cleaner energy sources that support more resilient operations and energy systems.

1. More than 300 new mines required to meet battery demand by 2035 | Benchmark Intelligence
2. Global Mining & Metals Greenhouse Gas (GHG) Emissions Dataset | ICMM

The sector is already advancing towards low-carbon operations through a set of complementary decarbonisation pathways, including improving energy efficiency, electrifying equipment, integrating renewable power, adopting lower-carbon fuels and deploying emerging technologies. However, the success of these individual decarbonisation efforts is interdependent with factors that extend beyond mining companies' direct control. System-level support and cross-sector collaboration are essential to enabling site-level ambition and can act as multipliers for scaling to industry-wide decarbonisation. Without action beyond the mine fence – including access to affordable and reliable clean energy, timely and efficient permitting processes for renewable energy and enabling infrastructure, the creation of policy frameworks, and coordinated infrastructure investment – fragmentation prevails and progress is likely to stall.

Central to this is recognising the pivotal role mining can play in transforming national and regional energy systems and understanding that transformed energy systems are integral to regional mining industries' future global competitiveness. Realising this potential requires mining to be fully integrated into energy planning, strategic climate policy development and an enabling policy framework that mitigates execution risk. This is not simply a 'nice to have' – it cannot be overstated how important it is to understand the mining sector's clean energy demand, the attendant market opportunity and the significance of policies encouraging plans that translate into bankable projects. These are fundamental to broader, system-level decarbonisation efforts, as well as presenting substantial commercial opportunities for stakeholders if managed effectively.

For energy providers and infrastructure developers, there are opportunities to secure long-term stable revenues through contracted supply of clean, renewable energy, within a broader enabling framework. For mining companies, it enables access to reliable, cost-competitive energy – reducing exposure to fuel-price volatility and supporting more resilient operating margins. More broadly, these integrated approaches can improve access to capital, lower the cost of financing, stimulate innovation and position early movers to capture additional value as low-carbon energy systems scale.

Benefits for different actors across the value chain include:

— **Strategic resilience for mining companies:** enhanced energy security, cost stability and operational resilience while improving long-term cost competitiveness.

— **Anchor benefits for communities:** catalysed local energy access in remote regions, as well as shared socioeconomic development and resilience opportunities. These will ultimately also support enhanced social licence for mining operations.

— **Governments' green industrialisation agenda:** aligning policy with market and climate priorities, attracting inward capital investment into domestic industries, creating skilled jobs, strengthening energy security and modernising energy grids through integrated infrastructure development.

— **Investors' pipeline:** access to a growing pipeline of bankable, low-carbon infrastructure and industrial assets while de-risking portfolios through exposure to predictable long-term contracted revenues and policy-aligned investments, gaining exposure to a growing market for sustainable assets.

— **Scaling markets for Original Equipment Manufacturers (OEMs):** accelerating innovation and expanding markets for electric and energy-efficient mining equipment and alternative fuels, as demand shifts towards lower-carbon, energy-resilient operations.

— **Collaboration driven by international organisations:** convening stakeholders, supporting cross-border frameworks and harmonised standards, mobilising finance and aligning climate, development and industrial strategies across regions.

Responsible, low-carbon mining must deliver a return on investment (ROI) both for mining companies and the above stakeholders. For these stakeholders to build productive partnerships and cooperate effectively towards the goal of responsible, low-carbon mining, risks must be distributed and investments must deliver an acceptable return. Decarbonising at the scale needed to meet global climate commitments means that clean energy solutions must support – not undermine – operational profitability. Clear business drivers, cost competitiveness and investable policy frameworks are essential to ensure responsible mining remains commercially viable while accelerating the energy transition.

This report highlights the main site and system-level challenges facing mine decarbonisation, specifically relating to Scope 1 and Scope 2 emissions and suggests practical actions to overcome them. It draws out four unifying and globally relevant key enablers that, when adapted for the context and working in unison, will drive progress in both the short and long term, including:

— **Technological innovation and deployment with flexible frameworks**, which allow site-appropriate electrification, renewable integration and advanced efficiency measures to be implemented at scale.

— **Mine design and next-generation thinking**, which embed future-ready energy systems, modularity and circular practices from the outset.

— **Context-relevant investment models**, which mobilise capital, share risk and attract private and public finance.

— **Supportive policies**, regulations and international agreements, fit for context, which encourage key markets' development and provide clarity, consistency and confidence for investment and collaboration.

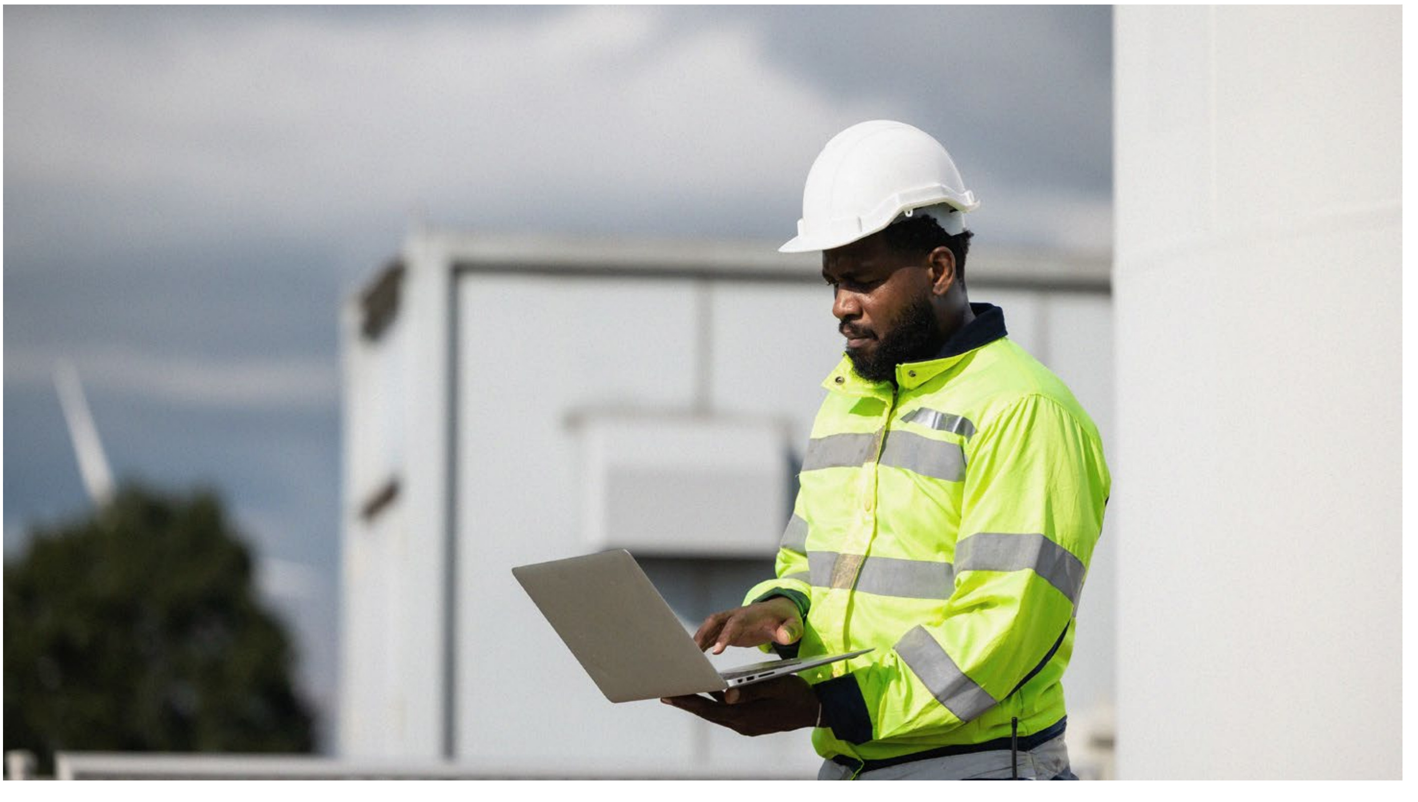
To supercharge the much-needed coordination between these enablers to achieve their potential, the report outlines as number of key principles around two points of accountability:

Operational Transformation	Systemic Transformation
Addressing internal constraints and leveraging incentives to make site-level action the path of least resistance.	Building the external architecture required to normalise and accelerate low-carbon industrial growth.
✓ **Principle I. Integrating the Operation and Reforming Finance:** Mining companies must overhaul internal structures to support systemic integration. ✓ **Principle II. Accelerating Learning and Replicable Solutions:** Mining companies must move from experimentation to scaled deployment, enabled by shared learning and collaboration, and adopt a cultural shift towards shared progress.	✓ **Principle I. Context-Sensitive Scalability:** Transformation fails when technology deployment attempts to move faster than the finance, systems and people required to support it and is most effective when enablers are calibrated to local realities. ✓ **Principle II. Systems-Integrated Planning and Strategic Alignment:** This ensures that the goals of mining companies, financiers and governments move in a unified direction. ✓ **Principle III. Systemic Standardisation:** The sector must move beyond the current landscape of isolated 'one-off' projects towards a model of more replicated deployment in partnership. ✓ **Principle IV. Strategic De-risking:** This is the process of identifying, partitioning and allocating the diverse risks of the energy transition to the parties best positioned to manage them, fairly and as a combined effort. True de-risking requires a coordinated approach across political, technical, infrastructural and social domains.

The final sections of this report outline a focused, time-bound roadmap for collective action in the next 5–10 years, to create the conditions for fast-tracking and scaling decarbonisation for mine sites and capitalising on the opportunities to support broader system-level decarbonisation efforts. Immediate actions that all stakeholders should collaborate on to galvanise action in the next five years focus on:

1. **Embedding integrated energy and cost planning as standard practice**
   Mining companies, financiers and governments should adopt common energy-planning tools and total cost of ownership (TCO) approaches to guide investment decisions. This creates a shared evidence base for comparing electrification, renewables, low-carbon fuels and efficiency measures, and reduces uncertainty for investors.
2. **Scaling deployment through service-based and shared infrastructure models**
   Wider use of power purchase agreements (PPAs), energy-as-a-service models and shared infrastructure arrangements can reduce upfront capital requirements and accelerate deployment, particularly where mine assets have shorter lifecycles, or grids are constrained.
3. **Accelerating pre-competitive collaboration to de-risk technology adoption**
   Joint trials, shared standards and coordinated learning are essential to move solutions from pilots to deployment. Collaboration between mining companies, OEMs, energy providers and regulators can shorten learning curves and reduce duplication.
4. **Strengthening workforce capability and operational readiness**
   Decarbonisation at scale requires skilled operators, engineers and regulators. Coordinated workforce development across companies and regions is needed to support electrification, renewable integration and new operating models.
5. **Mainstreaming circular design and closed-loop practices**
   Circular approaches should be treated as a core efficiency lever, with circularity across key materials offering the potential to reduce emissions by up to 40% by 2050. At the mine-site level, this includes designing for refurbishment and upgrade, increasing reuse of components, and integrating recycling and material recovery to lower energy demand, reduce costs and enhance resilience.

Mining has the potential not only to support the energy transition but to accelerate it. By aligning internal capabilities with external systems across technical, financial, governance and timeline dimensions – supported by the enabling conditions described in this report – the sector can unlock rapid, large-scale decarbonisation and become a cornerstone of resilient, low-carbon economic development.



Introduction

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This report addresses a central challenge facing the sector: how to turn the growing opportunity around mine decarbonisation into consistent, scalable action at mine sites, and how to foster greater collaboration across the value chain so miners and other stakeholders can manage risk, mobilise investment and capture the value associated with system-level decarbonisation.

While proven technologies and emerging solutions are increasingly available, progress remains uneven. Unlocking this opportunity requires more than operational transformation alone. The pace of implementation is shaped not only by technical readiness but by the conditions beyond the mine gate that enable or constrain deployment, including access to finance, policy certainty, infrastructure, skills and coordinated planning.

Mining companies are already pursuing practical decarbonisation pathways, including improvements in energy efficiency, electrification of equipment, integration of renewable energy, use of low-carbon fuels, and the deployment of emerging technologies. These pathways are increasingly shaping how mining operations are designed, powered and managed.

Their successful deployment, however, depends on a set of enabling conditions that extend beyond individual sites. These include alignment across technical systems, financial structures, governance arrangements and timelines, as well as the broader key enablers that support a functioning system. Without this alignment, progress can be slowed by fragmented decision-making, infrastructure constraints and misaligned incentives.

When these conditions are in place, mine decarbonisation can move beyond a compliance-driven challenge and become a strategic opportunity, strengthening operational resilience, unlocking new investment and accelerating the deployment of clean energy infrastructure in and beyond the mine site, while enabling more coordinated planning, shared solutions and faster replication across regions.

Understanding and activating these enabling conditions is essential if the sector is to meet its commitments while continuing to supply the materials required for the transition it enables. In this context, mining has the potential to act not only as an energy consumer but also as a catalyst for wider energy-system transformation. As large, stable energy users, mining operations can act as anchor loads that help attract investment in renewable energy generation, storage and transmission infrastructure, particularly in remote regions. This can support improved access to clean energy for surrounding communities and other industries, contributing to broader socioeconomic development.

Mining's Dual Role in Transition and the Scale of Change

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The mining and metals sector plays a dual role in the decarbonisation agenda. It is a significant source of greenhouse gas (GHG) emissions and an essential supplier of the minerals required for clean energy technologies, electrified transport and modern infrastructure.[3]

Findings from ICMM's *Global Mining & Metals Greenhouse Gas (GHG) Emissions Dataset* indicate that the mining and metals sector accounted for around 11% of global GHG emissions in 2024, equivalent to approximately 6 gigatonnes (Gt) of CO_2e. Of this total, around 3% is attributed to primary mining activities (Scope 1 and 2 emissions), and around 8% to metal production.[4] While a significant share of emissions occurs in downstream processing activities across the value chain (around 8%), these are not always within the direct operational control of mining companies.

This report therefore focuses on emissions associated with mineral extraction and mine site operations, where mining companies have the greatest ability to influence decarbonisation outcomes.

At the operational level, emissions are largely driven by the energy-intensive nature of mining. Diesel use in haulage and on-site generation contributes a large share of direct emissions,[5] with electricity consumption for processing and ventilation accounting for a substantial proportion of indirect emissions, depending on grid carbon intensity.[6]

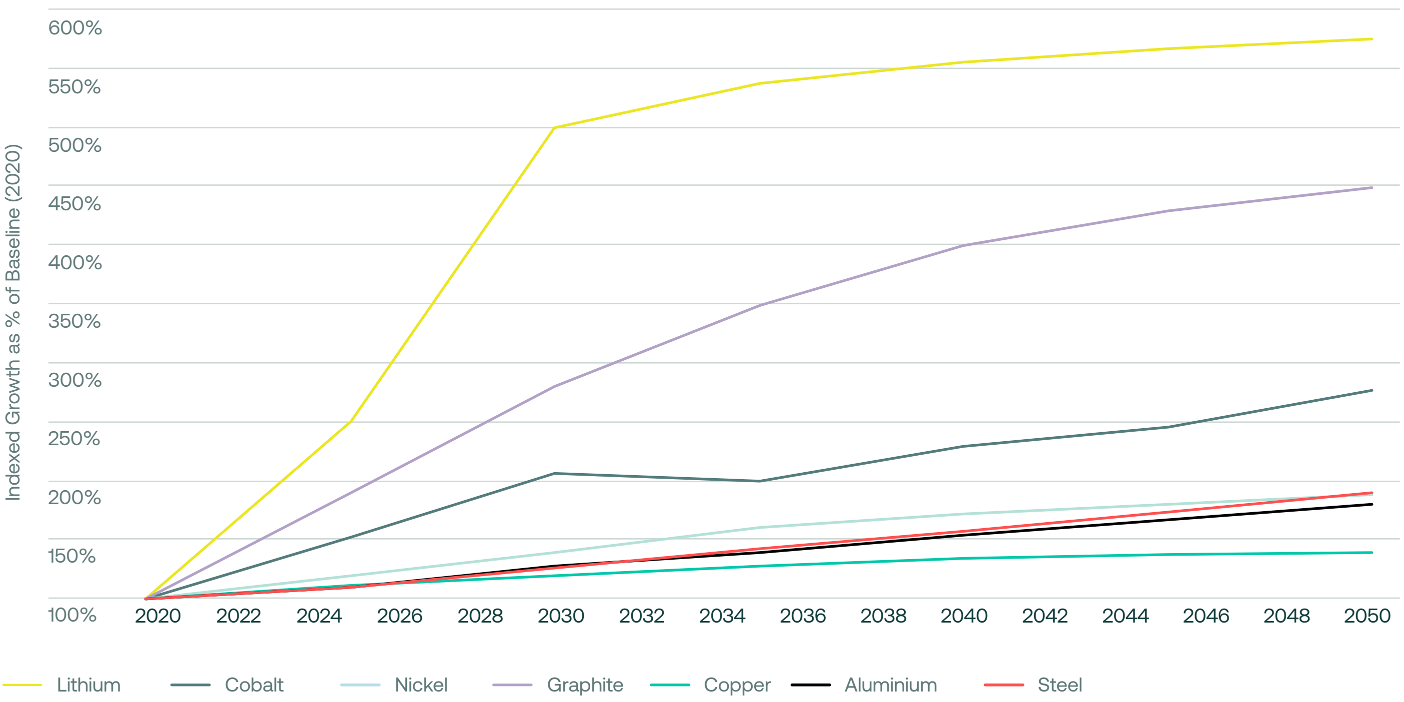
Fact box: Truck emissions at site

- Globally there are around **28,000** large-haul trucks in operation at mine sites, using **25bn** litres of diesel per year
- Diesel-powered haul trucks contribute **+69m** tonnes of CO_2 emissions a year, around **30-50%** of emissions at mine sites
- This is roughly the same volume of emissions as nearly **4m** first-class round-trip flights from London to Santiago

At the same time, demand for minerals is rising sharply. Clean energy technologies are materially more mineral intensive than their conventional counterparts. Electric vehicles (EVs) require significantly higher quantities of copper, lithium, nickel and cobalt than internal combustion vehicles, while renewable power generation and grid expansion depend on large volumes of metals and materials. Meeting this demand will require substantial growth in mining activity over the coming decades, with demand for critical minerals projected to increase by as much as four to six times by 2040.[7,8]

3. The role of critical minerals in clean energy transitions | International Energy Agency
4. Global Mining & Metals Greenhouse Gas (GHG) Emissions Dataset | ICMM
5 .Net zero roadmap for copper and nickel | International Finance Corporation, World Bank Group
6. Integrating clean energy into mining operations (U.S. Department of Energy, Technical Report No. 82537) | National Renewable Energy Laboratory
7. More than 300 new mines required to meet battery demand by 2035 | Benchmark Intelligence
8. The role of critical minerals in clean energy transitions | International Energy Agency

Figure 1: Relative demand trajectories of select metals and minerals, indexed 2020 = 100% (IEA)



This combination of rising demand and existing emissions intensity creates both risk and opportunity. Without accelerated decarbonisation of operations, the sector could undermine global climate goals and face higher regulatory and cost pressures, while misaligned operators risk losing access to emerging low-emissions supply chains. Conversely, proactive decarbonisation strengthens investor confidence, supports social licence to operate and enhances longterm competitiveness and operational resiliency.

Decarbonisation Pathways and Current Progress

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Decarbonisation pathways are the concrete operational transitions – including specific design choices, technologies, fuels and energy systems deployed at site level – to achieve meaningful progress towards Scope 1 and 2 net zero emissions in the mining and metals sector.

While technical readiness, financial structures, governance arrangements and timelines are critical, they must be applied in support of pathways that respond to local operating conditions and system constraints, as shaped by contextual factors such as regional conditions, commodity characteristics and energy system dynamics (see Section 5).

Across surface and underground operations, in both brownfield and greenfield contexts, companies are already pursuing different combinations of pathways to reduce emissions, reshape operating cost structures, lessen exposure to fossil-fuel price volatility and strengthen the long-term operational resilience of mining operations. The most commonly applied decarbonisation pathways are described below.

Energy efficiency and demand reduction

Energy efficiency and demand reduction offer an immediate and widely applicable pathway for reducing emissions across mining operations. By lowering overall energy consumption, efficiency measures reduce direct emissions and limit the scale of future investment required for electrification and clean energy supply. At scale, improvements in energy efficiency can deliver emissions abatement of approximately 5–10%, while remaining commercially viable and relatively low risk.[9]

Practical measures include optimising pit layouts and haul routes, improving ventilation systems, upgrading legacy equipment and minimising idling through better fleet management. These actions can be deployed quickly across a wide range of operating contexts and provide a strong foundation for other decarbonisation pathways by reducing baseline energy demand.

Electrification of mobile and stationary equipment

Electrification is a central pathway for addressing direct Scope 1 emissions, particularly from diesel-powered mobile equipment, which can account for a significant share (30–50%) of site-level emissions.[10] Electrifying haul trucks, loaders, drills and stationary equipment offers the potential for substantial, longterm emissions reductions, especially where electricity supply can be progressively decarbonised.

While electrification is technically feasible across most equipment categories, deployment remains uneven. Barriers include commercial readiness of battery electric vehicle (BEV)/hybrid electric vehicle (HEV) replacements for large-surface trucks and heavy equipment, the availability of charging infrastructure, power distribution constraints and the need to redesign operating models. As a result, this pathway is most effective when

9. Net zero roadmap for copper and nickel | International Finance Corporation, World Bank Group
10. Battery electric trucks emit 63% less GHG emissions than diesel | International Council on Clean Transportation.

sequenced alongside energy system upgrades and equipment lifecycles i.e. accounting for end of life, second- or after-life considerations, workforce capability development and supplier readiness. Early adoption also supports broader system readiness by accelerating technology development and reducing risk for subsequent deployments.

Integration of renewable and low-carbon power

Access to low-carbon electricity underpins many decarbonisation pathways in mining. Renewable and low-carbon power reduce Scope 2 emissions directly and enable emissions reductions from electrified fleets and processes. In grid-connected regions, this pathway may involve changes to procurement, investment in on-site generation or participation in grid upgrades. In remote or weak-grid locations, on-site renewable energy and hybrid systems are often the primary option.

Declining costs for solar, wind and battery storage[11] have improved the feasibility of these solutions, and hybrid systems are increasingly competitive with diesel or gas generation. However, feasibility remains highly dependent on local conditions. Constraints such as limited transmission capacity, grid stability requirements and variability management continue to influence deployment feasibility. Effective integration therefore requires solutions that are tailored to local load profiles, grid characteristics and resource availability.

Use of low-carbon liquid fuels as transitional solutions

Low-carbon liquid fuels provide an important pathway where electrification is not yet technically or commercially viable. This is particularly relevant for heavy mobile equipment, long-haul applications and remote operations. Options include biodiesel, renewable diesel and, in specific contexts, compressed natural gas.

Biodiesel and renewable diesel are especially attractive as near-term solutions because they can be used as drop-in fuels with minimal equipment modification, and can deliver significant lifecycle emissions reductions.[12] While fuels such as renewable natural gas and green hydrogen offer longer-term potential, their scalability remains limited in the near term by cost, supply availability, production capacity and infrastructure readiness. For example, green hydrogen production costs typically range between US$3–8/kg today, while renewable natural gas can exceed US$15–30/MMBtu (1m British thermal units),13 depending on region and feedstock availability, compared to lower and more volatile prices for conventional natural gas. As a pathway, low-carbon liquid fuels can deliver early emissions reductions while enabling a managed transition towards electrified systems.

Innovation and deployment of emerging technologies

Sustained decarbonisation requires ongoing innovation and testing to advance deployment of emerging technologies across mining operations. This pathway extends beyond individual technologies to include the operational capabilities, partnership models and procurement approaches needed to support experimentation, learning and managed risk-taking.

Compared with other energy-intensive sectors, mining has often adopted new technologies only once they are fully commercial. Given the scale and urgency of the transition, greater engagement earlier in the technology development cycle is required to accelerate cost curves and improve future deployment readiness. Proactively engaging with emerging technologies is critical for accelerating cost reductions, enabling learning curves and securing competitive advantage in future low-carbon value chains.

Ecosystem integration and regional policy drivers

Beyond site-specific technical innovation, significant progress is being realised through the integration of mining operations into regional, industrial, economic-corridor developments. These frameworks transition the sector away from 'islanded' mines towards a model in which mining acts as an anchor energy user and investment partner.

In jurisdictions where regional infrastructure bottlenecks and grid constraints persist, mining companies are leveraging their large-scale, stable demand to catalyse common-user infrastructure, including electrified rail networks and cross-border renewable zones. OEMs and service providers pursuing road-freight decarbonisation are also benefiting from new energy nodes offered by transitioning mines as well as new energy nodes in these corridor systems.

By synchronising decarbonisation with in-country value addition and regional beneficiation, these models utilise strategic de-risking and shared delivery mechanisms to

11. Renewable Power Generation Costs in 2023 | International Renewable Energy Agency (IRENA)
12. Biodiesel Benefits and Considerations | U.S. Department of Energy, Office of Critical Minerals and Energy Innovation
13. Global Hydrogen Review 2025 | International Energy Agency (IEA)

justify capital-intensive transitions. This integration fosters the green lead in markets required for competitive industrial performance, effectively transforming site-specific pilots into standardised, regional, industrial solutions.

Current progress and efforts under way

Meaningful progress towards mine site decarbonisation is already happening and early movers are realising benefits through reduced energy costs, improved resilience, and stronger environmental, social and governance (ESG) performance.

Renewable energy integration is expanding rapidly, with more than 5 gigawatts (GW) of renewable power now supplying mining operations worldwide.[14,15] Solar projects in Chile,[16] Australia[17] and South Africa[18] are enhancing energy resilience by reducing reliance on fossil fuels and lowering energy costs, thanks to advancements in solar and storage technologies.

Fleet electrification is also advancing. Battery-electric haul trucks, trolley-assist systems and alternative fuel solutions are being trialled across commodities and regions.[19] Electrification can significantly reduce Scope 1 emissions from diesel use in mobile equipment, recognising, it may also increase Scope 2 emissions, where operations rely more heavily on grid electricity. In this sense, electrification can shift emissions from direct on-site fuel combustion (Scope 1) to purchased electricity (Scope 2), particularly where the power supply remains carbon intensive.

While emissions outcomes depend on the carbon intensity of electricity supply, this should be assessed through a medium- to long-term lens. As power systems decarbonise and infrastructure develops, grid emission factors are expected to decline, meaning that electrification not only reduces operational diesel dependence but also positions mine sites to benefit from the use of lower-carbon electricity over time. This strengthens the case for electrification, even where near-term electricity supply remains partially fossil-based.

Momentum is also building through coordinated first-mover initiatives. Surface haulage remains the largest source of site-level emissions[20] and collaborative efforts have materially accelerated learning curves and readiness expectations for zero-emission haul trucks. CEO-led, pre-competitive collaboration between miners and equipment manufacturers – such as ICMM's Innovation for Cleaner, Safer Vehicles (ICSV) Initiative[21] – as well as the development of shared charging standards and safety frameworks, have helped advance interoperability and deployment of solutions. Integration of electrification with operational safety systems has been critical in maintaining performance and workforce confidence as fleets transition.

Learning at speed has become a defining feature of recent progress. Site-led trials[22,23], shared technical guidance[24,25] and coordinated innovation forums[26,27] are helping to reduce duplication, spread proven approaches and lower risk for subsequent adopters.

14. Renewable Power Generation Costs in 2023 | International Renewable Energy Agency
15. Integrating clean energy into mining operations (U.S. Department of Energy, Technical Report No. 82537) | National Renewable Energy Laboratory
16. Mining with principles at Anglo American's Los Bronces copper mine | ICMM
17. Mining with principles at Gold Fields' Granny Smith mine | ICMM
18. The South Deep Khanyisa solar plant | Gold Fields
19. Battery electric trucks emit 63% less GHG emissions than diesel | International Council on Clean Transportation
20. Pulling the Weight of Heavy Truck Decarbonization | Rocky Mountain Institute, 2019
21. More OEMs join the ICMM's Innovation for Cleaner and Safer Vehicles initiative | International Mining, Nov 2020
22. Collaboration for Innovation: Accelerating the Implementation of Zero Emission Vehicles for the Mining and Metals Industry | ICMM, Nov 2022
23. Accelerating the Adoption of Zero-Emission Haul Trucks in the Mining and Metals Industry | ICMM, Dec 2023
24. Diesel Particulate Matter (DPM) Good Practice Guide | ICMM, Dec 2024
25. Celebrating a second year full of accomplishments in the CharIN-ICMM Project Mining | CharIN, March 2025
26. The art of the possible: How collaboration is driving the transformation of large haul truck fleets | ICMM, Aug 2024
27. Reflections from Sweden: Collaboration to advance cleaner, safer mining | ICMM, Oct 2025

Key Considerations

05

Delivering a just and effective energy transition in mining depends not only on technical solutions and financial structures, but also on the broader context in which decarbonisation takes place. These contextual factors shape what is feasible, how quickly change can occur, and which pathways are most viable in practice.

Decarbonisation outcomes are influenced by a set of external conditions that sit beyond the control of individual sites but directly affect decision-making and implementation. These include geographic context, commodity characteristics, trade dynamics and the structure of local energy systems.

Ignoring these factors can result in misaligned strategies, higher costs and delayed implementation, while integrating them into planning enables more realistic, resilient and scalable transition pathways.

Commodity specifics

Not all minerals present the same challenges. The type of material dictates energy intensity, demand growth and decarbonisation pathways. Demand for transition minerals shows markedly different growth profiles to 2050, with lithium rising fastest and copper increasing more steadily, while bulk commodities remain essential for infrastructure and renewables but face heightened scrutiny due to energy-intensive production pathways.[28, 29]

- **Copper** demand is projected to rise by 40% by 2050 due to grid expansion and electric mobility.
- **Cobalt** demand is forecast to reach 350,000 tonnes annually by 2030, up from 170,000 tonnes in 2020, and to rise a further 76% by 2050.
- **Lithium** demand will surge by more than 400%, driven by battery technologies.
- Bulk commodities such as **iron ore** and **aluminium** remain in high demand for infrastructure and renewable installations, but their production pathways are energy-intensive and attract growing scrutiny.

These differences ripple through supply chains. Downstream buyers increasingly signal expectations: under the World Economic Forum's First Movers Coalition, major consumers of steel and aluminium have pledged that at least 10% of their purchases will meet near-zero emissions thresholds by 2030. Similar commitments for copper or battery metals would attach premiums to low-carbon supply chains and accelerate investment in decarbonisation. Tailored approaches to commodity specifics guide the conversation towards how international exchange and policy overlay influence costs and technology access.

28. Global critical minerals outlook 2025 | International Energy Agency
29. Cobalt 2050: Unlocking potential for a net-zero future | Cobalt Institute

Trade and tariffs

International commerce can either smooth the path to decarbonisation or place obstacles in its way. Tariffs, trade restrictions and the design of agreements alter the cost and supply of technologies and components essential for clean mining.

Recent measures (at the time of publication) illustrate the challenge:

- The US has raised tariffs on Chinese EVs to 100% and imposed duties of 25% on EV batteries and 50% on solar cells.[30]
- The EU has applied tariffs of 17–38% on Chinese EVs.[31]
- Canada has introduced a 100% surtax on Chinese EVs.[32]

These actions raise landed costs, constrain supply and complicate procurement for mining companies seeking electrification and renewable installations. At the same time, mechanisms such as the EU Carbon Border Adjustment Mechanism (CBAM) incentivise low-carbon production but require miners to anticipate compliance costs and shifting trade flows.

Trade policy can also encourage responsible behaviour when linked to market access, export licences or preferential terms, reinforcing incentives for low-carbon operations.

The interplay between cross-border flows, technology costs and market access feeds naturally into considerations of where and how power is supplied – the final key dimension of context.

Energy system context

The structure and availability of energy systems is a fundamental determinant of decarbonisation feasibility. Whether a mine is grid-connected or operates off-grid significantly affects technology choices, investment requirements and transition timelines.

Mines within established electricity networks may access cleaner power through supplier switching, grid decarbonisation or direct procurement mechanisms. However, grid-connected sites often face constraints related to connection delays, limited transmission capacity and the carbon intensity of existing supply.

For many operations, particularly in remote locations, access to grid electricity is limited or unavailable. These sites must develop integrated on-site energy systems, often combining renewable generation, energy storage and backup generation in hybrid configurations.

Many sites face barriers to affordable, reliable clean energy because transmission capacity is limited or absent. A recent industry survey found that 68% of miners cite inadequate charging and power infrastructure as the main constraint to electrifying equipment.[33] The B2Gold Fekola Mine in Mali demonstrates how this challenge can be met: a 30 MW solar farm paired with a 15.4 MWh battery supplies up to 75% of daytime power to an off-grid site, with a design that allows expansion or relocation. Elsewhere, the Weipa Solar Farm in Australia feeds both the mine and the town of Weipa under a PPA,[34] illustrating how off-grid installations can serve adjacent communities and build social licence. For grid-connected sites, the challenge is different: energy may be available but derived from coal or gas. Here, engagement in system planning with utilities, modern tariff structures and on-site generation are key to lowering carbon intensity.

30. U.S. Trade Representative Katherine Tai Delivers Remarks on Her Actions to Increase China Tariffs | Office of the United States Trade Representative
31. Commission imposes provisional countervailing duties on imports of battery electric vehicles from China | European Commission
32. Surtax on Chinese-made Electric Vehicles | Government of Canada, Department of Finance Canada
33. The Electric Mine | Mining Magazine
34. Weipa 6.7MW Solar Photovoltaic (PV) Solar Farm | ARENA, Australian government

For grid-connected sites, the challenge is often less about access to electricity and more about the ability to secure timely, reliable, affordable connections and reduce the carbon intensity of supply. The Soaring Power Demand report notes that, in mature systems such as Europe and the US, many large power transformers at substations are close to or exceed their typical 45-year design life, and that equipment demand is driving up costs. It also reports that demand for US generation step-up transformers rose by 274% between 2019 and 2025, contributing to supply pressure and investment in new manufacturing capacity. These constraints can translate into longer lead times for grid upgrades and new connections, and reinforce the importance of early engagement with network planners, realistic sequencing of electrification plans and consideration of on-site generation or hybrid configurations where connection delays are material.[35]

Energy context interacts with all other considerations. Finance models must reflect the cost and risk of bespoke systems or grid upgrades. Technology must be selected for modularity, scalability and compatibility with evolving network and charging requirements. Trade conditions affect component availability and lead times, including for critical grid equipment. Regional factors dictate the degree of government support and the feasibility of public–private coordination. Understanding these relationships is essential for designing effective transition plans that remain deliverable under constrained infrastructure conditions.

Competition for energy from emerging industries

Demand for clean, reliable power is increasing rapidly as new energy-intensive industries, particularly data centres and advanced manufacturing, expand their operations. This shift creates both a challenge and an opportunity for the mining sector. On one hand, competition for scarce energy resources may intensify cost pressures and constrain the availability of low-emissions power for mine operations, particularly in regions where transmission capacity is already limited. On the other, it creates an incentive for mining companies to position their sites as integrated energy and innovation hubs capable of supporting these new industries.

Recent analysis highlights how quickly data-centre demand is reshaping power systems in some markets. Global electricity consumption from data centres is forecast to double to 945 TWh by 2030, and data centres are expected to account for nearly half of the US's electricity demand growth to 2030, according to the International Energy Agency (IEA). Furthermore, large data-centre owners are investing in generation and grid infrastructure to secure 24/7 electricity supply, including renewables, storage and firm generation. These dynamics add a new layer of competition for capacity and can accelerate investment in generation, storage and network upgrades in locations that can accommodate large loads.[36]

Several regions are already experiencing pressure on grids due to the fast growth of data centres. In such contexts, mines that can offer flexible demand profiles, large land footprints and established infrastructure have the potential to become anchor loads within new or upgraded energy systems. This model can enable shared investment in renewable generation, storage and transmission, reducing costs and unlocking co-benefits for surrounding communities and industries. Given that some developers are seeking to co-locate clean energy projects with data centres to reduce long waits for grid connections and manage transmission constraints,[37] integrated planning for co-location is increasingly relevant for mine sites.

The interaction between mining and emerging high-demand industries has implications across the transition landscape. Finance models need to account for the potential of co-investment or shared-use assets. Technology choices must consider compatibility with future sector-coupling arrangements. Trade dynamics may shift as data and digital service industries become new partners or competitors. Regional planning processes will need to integrate mining more proactively into broader energy development strategies. As energy ecosystems evolve, mines that can demonstrate flexible, low-emissions energy systems will be better positioned to attract investment and maintain operational resilience. When these considerations are understood and acted upon, they anchor the enablers within the reality of diverse contexts, ensuring that internal ambition co-evolves with external circumstances.

35. Harnessing renewables in Sub-Saharan Africa: Barriers, reforms and economic prospects | International Monetary Fund
36. Energy and AI | IEA
37. Energy and AI | IEA

Barriers Slowing Mining Decarbonisation

06

Today, the primary barrier to the mining sector's clean energy transition is no longer a lack of technology but a lack of deployment architecture and coordinated drivers and actors.

The pace of change is constrained by an implementation gap rooted partly within company operations. While aspects of the decarbonisation pathway are technically 'controllable', they often collide with deep-seated industrial habits and internal financial structures. These include capital competition, gaps in technical expertise, management preferences and uncertainty over equipment costs and interoperability. Addressing these internal frictions is essential to ensuring coherence and mainstreaming decarbonisation at the site level.

However, the challenge extends substantially beyond the mine's sphere of control. The mining sector is dotted with lighthouse projects – operations that have achieved remarkable levels of decarbonisation through extraordinary effort, bespoke financing and one-off regulatory workarounds. Operational efforts without a supportive systemic framework keep development to pilot scale, with companies reaching a technical ceiling they cannot break through alone.

The transition to a low-carbon mining sector is an execution and scaling challenge that demands concerted alignment across the value chain.
The window for this coordinated action is rapidly narrowing. Infrastructure investment cycles, power-system expansions and fleet replacement decisions made this decade will lock in emissions and cost structures for the next 20–30 years. Identifying and activating drivers for change today is therefore not an analytical exercise – it is a strategic necessity to avoid locking in higher-cost, higher-emissions pathways.

While context-specific solutions are needed to address local risks, the broader systemic barriers are fairly universal: high upfront capital requirements, uncertainty around total cost of ownership (TCO), skills shortages, permitting delays and fragmented policy environments all slow deployment. In some regions, political instability and governance challenges add further risk, particularly where access to reliable clean energy is constrained.[38] Crucially, barriers across finance, policy, regulation, infrastructure, skills and collaboration can reinforce one another.

Isolated efforts to address these challenges have minimal potential for integration with wider transition enablers such as power-system expansion, infrastructure development and coordinated policy frameworks. Currently, effectiveness of efforts to address these barriers varies significantly across regions. (Further detail on regional differences provided in Annex 3).

38. Harnessing renewables in Sub-Saharan Africa: Barriers, reforms and economic prospects | International Monetary Fund

Enablers and the Supporting Ecosystem

07

Successful decarbonisation depends on a broader enabling ecosystem that extends beyond individual organisations. Four key enablers shape both near-term progress and long-term outcomes. Their relevance lies not in their novelty, but in how they interact with local contexts, influence investment decisions and determine the pace at which decarbonisation pathways can be implemented and scaled.

These enablers span finance, policy, regulation, infrastructure, skills and international collaboration, and their effectiveness varies significantly across regions. In some jurisdictions, strong policy frameworks and access to capital accelerate deployment. In others, infrastructure gaps, regulatory uncertainty or limited institutional capacity constrain progress. (See Annex 3 for more detail).

The four key enablers are as follows:

- **Technological innovation and deployment**, which enable electrification, renewable integration and advanced efficiency measures to be implemented at scale.
- **Mine design and next-generation thinking**, which embed future-ready energy systems, modularity and circular practices from the outset.
- **Innovative investment models**, which mobilise capital, pool risk and attract private and public finance.
- **Supportive policies, regulations and international agreements**, which encourage key markets' development and provide clarity, consistency and confidence for investment and collaboration.

Ensuring the coordination of these four enablers depends on the complementary roles of different stakeholders across the mining and energy ecosystem. Mining companies act as anchor energy users and investment partners, integrating decarbonisation into operational planning and helping catalyse new energy infrastructure. Governments provide policy certainty, regulatory alignment and long-term infrastructure planning, while energy providers and OEMs deliver the technologies and systems required for electrification and low-carbon energy. Financiers enable deployment by structuring capital, supporting new business models and reducing investment risk, while multilateral institutions facilitate coordination, provide technical assistance and mobilise concessional finance. Communities also play a critical role in shaping socially responsible outcomes and ensuring that local benefits are realised. (Further details on stakeholder roles and delivery mechanisms are provided in Section 11).

Identification of enablers already proving beneficial

Overcoming persistent barrier to decarbonisation requires a focus on enablers that provide the activating conditions and act as the structural bridge to overcome financial, regulatory, infrastructural and stakeholder risks and frictions. The sector needs enabling conditions that encourage companies to act when the power to do so lies within their domain, and that empower the sector to de-risk these efforts and move from a collection of 'heroic exceptions' to a standardised, global norm.

The value of identifying enablers is already visible in practice. First movers are realising benefits through reduced energy costs, improved resilience and stronger ESG performance. Strong and coordinated enablers also help ensure broader benefits accrue across the ecosystem:

— **Mining companies** gain operational resilience, cost stability and a strengthened social licence.

— **OEMs** can invest with greater confidence in low-carbon technologies.

— **Financiers** can better understand the sector's needs, de-risk portfolios and deploy capital at scale.

— **Governments** can align policy and infrastructure planning with credible investment signals, supporting jobs and regional development.

— **Multilateral institutions** gain leverage to coordinate action and harmonise standards.

Building the Conditions for Scaled Decarbonisation

08

To address the implementation gap, actors across the value chain need to consider two points of accountability:

1. **Operational transformation** – addressing internal constraints and leveraging incentives to make site-level action the path of least resistance.
2. **Systemic transformation** – building the external architecture required to normalise and accelerate low-carbon industrial growth.

Operational Transformation: Principles and Enablers

Operational transformation involves maximising the decarbonisation levers within a mining company's direct sphere of control. However, for these efforts to achieve industry-wide scale, companies must:

1. **Move from isolated site-level approaches** ('mines as islands') to viewing mine decarbonisation within the context of a broader industrial ecosystem, acting as both an anchor offtaker and a driver of new energy infrastructure.
2. **Shift to collaborative models**, establishing internal and external, cross-sector structures with aligned incentives.
3. **Accelerate the speed of learning** between companies and across sectors, sharing replicable solutions fit for specific contexts and technology choices.

This requires operational transformation considering the following two principles and supporting enablers:

Principle I. Integrating the Operation and Reforming Capital Allocation

— **Address Workforce Energy Literacy:** A persistent internal barrier is the gap between mechanical mining expertise and modern power-system management. Most mines are staffed by top-class mining, mechanical and geological engineers – not yet by power-system engineers. A site's ability to transition is therefore effectively capped by the energy literacy of its operational staff and the quality of its advisers in power electronics, battery management and renewable integration.

This applies at the operational level, where decarbonisation is viewed as a corporate sustainability task disconnected from site energy planning and performance, rather than a central site requirement.

— **From Siloed Sustainability and 'Island' Planning to Lifecycle and Ecosystem Integration:** Traditionally, mines have operated as independent energy consumers focused on power security and cost control. Progress requires viewing the mine as both an anchor offtaker and a driver of new infrastructure. Aligning mine design with regional energy planning, can unlock development that benefits the operation, nearby communities, and wider industrial corridors.

To manage dependency risk, mines can pursue phased compatibility rather than full reliance on external systems. Modular, grid-ready designs – such as containerised storage and scalable microgrids – maintain near term autonomy while enabling synchronisation with regional infrastructure as it develops, with modularity acting as a core risk mitigation tool.

— **Adopt Financial Model Reform (total cost of ownership (TCO) and Infrastructure):** Traditional capital allocation often prioritises short-term returns. Slow adoption of lifecycle-based financial models is rooted in the decisions of project hurdle rates, payback periods and separate CapEx to operating expenditure (OpEx) budget holders – all of which effectively disqualify capital-intensive energy investments needed for transition. Pragmatic energy planning requires a shift towards TCO and Levelized Cost of Energy models that clarify costs and benefits of low-carbon alternatives over the mine's life and making energy availability and carbon intensity primary parameters for ore-body evaluation and mine-planning. This approach enables valuation of negative externalities like carbon taxes, and potential upsides like strategic access to green offtakers, as well as capturing the volatility of energy pricing. Implementing these changes allows companies to align internal incentives and treat energy systems as long-term infrastructure assets rather than immediate operational expenses.

Principle II. Accelerating Shared Learning and Scalable Solutions

The final component of operational accountability is the move from experimentation to scaled deployment, and a cultural shift towards shared learning.

— **Proactive OEM Co-Design:** Companies should move away from transactional equipment procurement and towards collaborative models. This involves establishing cross-sector structures with OEMs to develop energy-resilient platforms that ensure interoperability and long-term modularity.

— **Speed of Learning:** Mining companies must accelerate the exchange of technical and operational data between sites and across the sector. By sharing replicable solutions – fit for specific geographical and technological contexts – the industry can reduce the early-adopter risk and lower the barriers to entry for all participants.

— **Standardisation of Choices:** Collaborative efforts to standardise technology choices (such as charging infrastructure or biofuel compatibility) ensure that site-level actions contribute to a scalable, global norm rather than a series of incompatible bespoke systems.

— **Localised Circularity:** At the site level, context-sensitive scaling involves designing for refurbishment and upgrade. By increasing the reuse of components and integrating closed-loop practices, mines can lower costs and energy demand in a way that respects local material availability and logistical constraints.

— **Defining the Pre-Competitive Boundary:** While protecting competitive advantage remains vital, the energy transition presents shared technical and structural barriers. By defining pre-competitive zones, companies can lower costs and risks without compromising their market position. Key enablers are interoperability; standardising interfaces to lower OEM-specific risks; sharing safety and environmental data to safeguard the sector's social licence; and exchanging non-proprietary performance data across climates to reduce redundant trials and speed up deployment.

Systematic Transformation: Principles and Enablers

Achieving sector-wide progress relies on synchronising what happens at mine sites with the broader financial, policy and infrastructure context. The foundation for success lies in creating an environment where these elements reinforce one another, allowing innovation to scale and investment risks to be reduced. Several themes introduced under operational transformation reappear in this section, reflecting the fact that many enablers must be strengthened at multiple levels simultaneously. While operational transformation focuses on actions within company control, systemic transformation addresses the wider market, institutional and regional conditions required for those same enablers to scale across the sector.

This section outlines four principles and the key enablers to deliver the systematic transformation needed, ensuring that decarbonisation is treated as a coordinated and scalable reality.

Principle I. Context-Sensitive Scalability

Transformation fails when solutions seek to impose changes that require radically rewiring policy and processes, or technologies are not best fit for the region and realities. The following four key enablers are at the heart of sector-wide transition, while their effectiveness depends on how they are calibrated to local realities:

— **Technological innovation and deployment:** Infrastructure development must consider applicable technologies that support electrification, renewable integration and advanced efficiency measures for implementation at scale. While there may well be contextual constraints, this should not lead to isolation or paralysing fragmentation. The focus should instead be on developing flexible frameworks that can be tailored for simple replication.

This will enable robust cross-sector learning, ensures that technology deployment is timed with the availability of infrastructure, encourages policy support and appropriate finance, and can help stimulate joint trials and coordinated learning between mining companies and OEMs.

— **Mine design and next-generation thinking:** Decarbonisation should be baked into the mine's spatial and operational DNA. For instance, for a greenfield project, this means designing 'electric-first' layouts, with steeper ramps, optimised for regenerative braking. For a brown-field site, it involves modular retrofitting; installing containerised battery storage that can be moved as the mine face advances.

— **Innovative investment models:** context relevant investment models must match the technological and stakeholder priorities, scale and risk coordination, and finance must adapt to regional risk profiles. At company level, capital allocation determines whether projects are approved internally; at system level, investment models determine whether sufficient pools of capital can be mobilised across the market. For instance, in different markets, the right fit may be a combination of blended finance, sovereign guarantees, sustainable finance, public private partnerships (PPPs), technology funds, or off-balance-sheet 'energy-as-a-service' (EaaS) models.

— **Supportive policies, regulations and international agreements:** Regulatory frameworks must be designed considering the local context to address local bottlenecks and provide investment confidence. For instance, in regions with ageing national grids, policy can prioritise wheeling, and for isolated regions, focus could be on mini-grid permitting to allow the mine to operate as a self-contained energy hub.

The power of these key enablers (and clarifying specific, common, regional and context-specific needs) lies in their interaction with the local environment. By identifying these context-specific drivers, we ensure that no site is viewed as so unique that it cannot draw lessons from elsewhere, and common requirements are expressed so that actors can begin to coordinate more effectively. (See Annex 2 for more detail on the alignment needed across different contexts beyond the mine-site).

Principle II. Systems-Integrated Planning and Strategic Alignment

System-wide strategic alignment ensures that the goals of mining companies, financiers and governments move in a unified direction. Where operational planning focuses on optimising individual sites and life-of-mine performance, systemic planning coordinates multiple actors, infrastructure timelines and policy cycles across regions.

Aligned systems create the conditions for collaboration and innovation, including service-based energy models – such as PPAs and other third-party arrangements – where external providers finance, build and operate energy infrastructure, as well as development corridors and shared infrastructure solutions (see Weipa Solar Farm case in Annex 2). Two key enablers for progress on alignment are:

— **Integrated Planning Tools:** Achieving alignment requires the adoption of common, system-level energy-planning tools with TCO approaches, to inform policymaking. At company level, TCO supports more effective project appraisal and mine planning; at system level, it creates a shared investment language that helps governments, utilities and financiers coordinate infrastructure and capital allocation. Consideration of proposed mine site energy needs over the Life of Mine (LOM) using TCO approaches can interface with energy planning and policymaking cycles. By mainstreaming integrated cost planning as a standard practice, the industry creates a predictable language for investment. With the establishment of a shared evidence base, stakeholders can accurately compare electrification, renewables and low-carbon fuels, removing the uncertainty that currently stalls investment decisions.

— **The System Circular Framework:** Strategic alignment must extend to material lifecycles, which go beyond a mine's control to the remit of local and national materials management and regulatory frameworks. By embedding circular considerations as a core efficiency lever, the sector can align emissions targets with resource conservation and other co-benefits. Integrating recycling and material recovery at the system level reduces overall energy demand and enhances the resilience of the entire industrial ecosystem.

Principle III. Systemic Standardisation

Currently, the ‘bespoke’ nature of mining decarbonisation and the minimal sharing of lessons and practices creates a steep learning curve for every new initiative, forcing developers, financiers, insurers and regulators to ‘re-learn’ the risk profile from scratch for every site and act as a barrier to the offering of more standardised solutions to the sector. Availability of skills is a factor that plays into this challenge.

Systemic standardisation is the mechanism that breaks this cycle. While operational standardisation simplifies deployment within individual projects, systemic standardisation creates repeatable markets across multiple projects, reducing transaction costs and accelerating replication. By creating a predictable, replicable environment and leaning in to coordinated learning curves and workforce readiness, decarbonisation can move from the realm of high-risk ‘special projects’ into a stable, infrastructure-grade asset class with the right skills to manage these future operations.

Three major enablers can help:

— **Technical Interoperability and Breaking Proprietary Silos:** A major hurdle to operational change is the fear of ‘technological lock-in’. Mining companies are often hesitant to commit to a specific manufacturer’s solution if infrastructure is proprietary and incompatible with other brands. However, addressing proprietary silos ensures that infrastructure – from charging interfaces to data protocols – is replicable across the sector, shortening learning curves and reducing costly duplication. There are two ways to address this:

- Open Standards for Infrastructure: Collaboration between mining companies and OEMs is essential to establish interoperable charging interfaces and battery protocols.
- Modular Infrastructure Templates: Developing ‘plug-and-play’ microgrid designs –where solar, wind and storage components are pre-configured – allows for rapid replication across different geographies. This reduces the need for expensive, site-specific-engineering.

— **Reducing Financier Fatigue and Risk Perceptions Through Replicability:** The primary drain on the speed of transition is often administrative and legal rather than technical. When every PPA or equipment lease is unique, the time and cost required for banks to conduct due diligence and approve financing become prohibitive.

- Standardised Contractual Frameworks: Developing industry-wide PPA templates and wheeling agreements reduce legal friction. This can allow financiers to move from evaluating one unique project to backing multiple projects simultaneously and learning across portfolios, drastically lowering the cost of capital.
- Common Risk Assessment Protocols: Standardising how the industry measures carbon abatement and ‘green value’ ensures that different lenders use the same metrics. This creates a transparent, liquid market for mining decarbonisation debt where the rules of the game are understood by all parties upfront.

— **A Focus on People and Skills:** Transformation fails when technology deployment moves faster than the systems and people required to support it. At operational level, workforce capability determines whether sites can safely operate new technologies; at systemic level, it determines whether enough engineers, technicians, trainers and regulators exist to support sector-wide deployment. Addressing this issue is largely pre-competitive, due to the scale of the need and if prioritising embedded local capacity.

- Sector Workforce Readiness: Operational synchronicity can benefit from standardised technical certifications and by partnering with local academic and vocational institutions to embed energy literacy into regional curricula. This can enable the industry to build a common competency framework for operators, engineers and regulators, and ensures that as new energy systems arrive, the local ecosystem possesses the skills to model, permit, operate and maintain them at scale.

Principle IV. Strategic De-Risking

Strategic de-risking is the process of identifying, partitioning and allocating the diverse risks of the energy transition to the parties best positioned to manage them. Operational risk management focuses on execution, uptime and integration at site level, whereas systemic de-risking addresses the political, regulatory, financing and infrastructure risks that determine whether projects proceed at all. True de-risking requires a coordinated approach across political, technical, infrastructural and social domains.

— **Political and Regulatory De-risking:** Policy volatility is a primary deterrent for long-term industrial investment. As noted in Annex 3 (Regional Differences), the maturity of the enabling environment drives the level of sovereign risk a mining and decarbonisation project carries. Key enablers include strategic alignment between mining and national industrial policy and clear national policies defining carbon frameworks with standardised permitting related to transition. They also include access to and availability of political risk insurance and sovereign guarantees to protect private capital from sudden regulatory shifts or pivots in national energy strategy.

— **Technical and Technology De-risking:** The deployment of first-of-a-kind technologies – such as hydrogen haulage or ultra-fast megawatt charging – introduces performance uncertainty that can stall site-level appetite. Performance-sharing agreements and technical standardisation could help, where OEMs assume technical performance risk through robust warranties and service maintenance models, and mining companies manage the operational integration risk, while technical assistance could be provided by multilateral bodies (detailed in Section 9) that help standardise the 'energy literacy' required to operate these systems safely.

— **Infrastructure and Supply-Chain De-risking:** Mining sites often face 'delivery risk' – the possibility that the required clean energy or alternative fuels (biodiesel, ethanol) will not be available when needed, or that the regional grid cannot support the load. Standardising the 'anchor tenant' model and common user infrastructure approach could help. In these arrangements, governments and utilities manage the macro-infrastructure risk (grid expansion), while mining companies de-risk the investment by acting as anchor offtakers, providing guaranteed long-term revenue. This mutual dependency ensures that infrastructure is built to scale, rather than in isolated, inefficient silos.

— **Social and Licence to Operate De-risking:** A systemic transition that fails to deliver local benefits creates significant social risk, potentially leading to operational delays or loss of social licence. Integrated socioeconomic development frameworks are essential. Through such arrangements, mining companies and local governments share the risk of just transition outcomes. By using mine-anchored energy infrastructure to provide regional power access, the social risk is shifted towards resilience against local unrest or political opposition.

System Alignment and its Dimensions

09

Section 8 identified the operational and systemic principles and enablers required to accelerate mining decarbonisation. However, the presence of these enablers alone does not guarantee delivery. Their impact depends on how effectively they are aligned across mine sites, energy systems, investment cycles and policy frameworks.

Without alignment, progress remains fragmented. Mining companies may electrify equipment, but without timely access to low-emissions power and appropriate permitting, those assets cannot operate as intended. Governments may set ambitious climate targets, but without mechanisms to mobilise capital, infrastructure and skills, delivery lags behind ambition. Alignment is therefore not optional. It is the condition that allows decarbonisation pathways to move from pilots to sustained deployment across sites and regions.

Alignment enables decarbonisation outcomes in four critical ways:

— **Enabling scalability:** Integrated systems and coordinated planning allow solutions to be replicated across sites, lowering costs and accelerating adoption.

— **Acknowledging interdependence:** Internal and external factors are mutually reinforcing. Fleet electrification depends on power availability. Renewable energy deployment depends on finance, land access and permitting.

— **Building resilience:** Alignment reduces exposure to policy volatility, infrastructure bottlenecks and market uncertainty by enabling more coordinated decision-making.

— **Fostering innovation:** Aligned systems create space for collaboration and new delivery models, including service-based energy solutions and shared infrastructure.

Integrated planning allows solutions to be replicated across sites, lowering costs and accelerating adoption. Coordination between internal and external actors reduces exposure to policy volatility and infrastructure constraints. At the same time, aligned systems create the conditions for collaboration and innovation, including service-based energy models such as PPAs and other third-party arrangements, where external providers finance, build and operate energy infrastructure, as well as demonstrating shared infrastructure solutions (see, for example, the Weipa Solar Farm case in Annex 2).

In practice, alignment refers to the synchronisation of decisions, systems and incentives across four key dimensions:

— **Technical alignment:** ensuring energy systems, equipment and digital infrastructure operate as one integrated, interoperable and future-ready system.

— **Financial alignment:** aligning capital strategies, procurement models and investment horizons with external financing structures and market expectations.

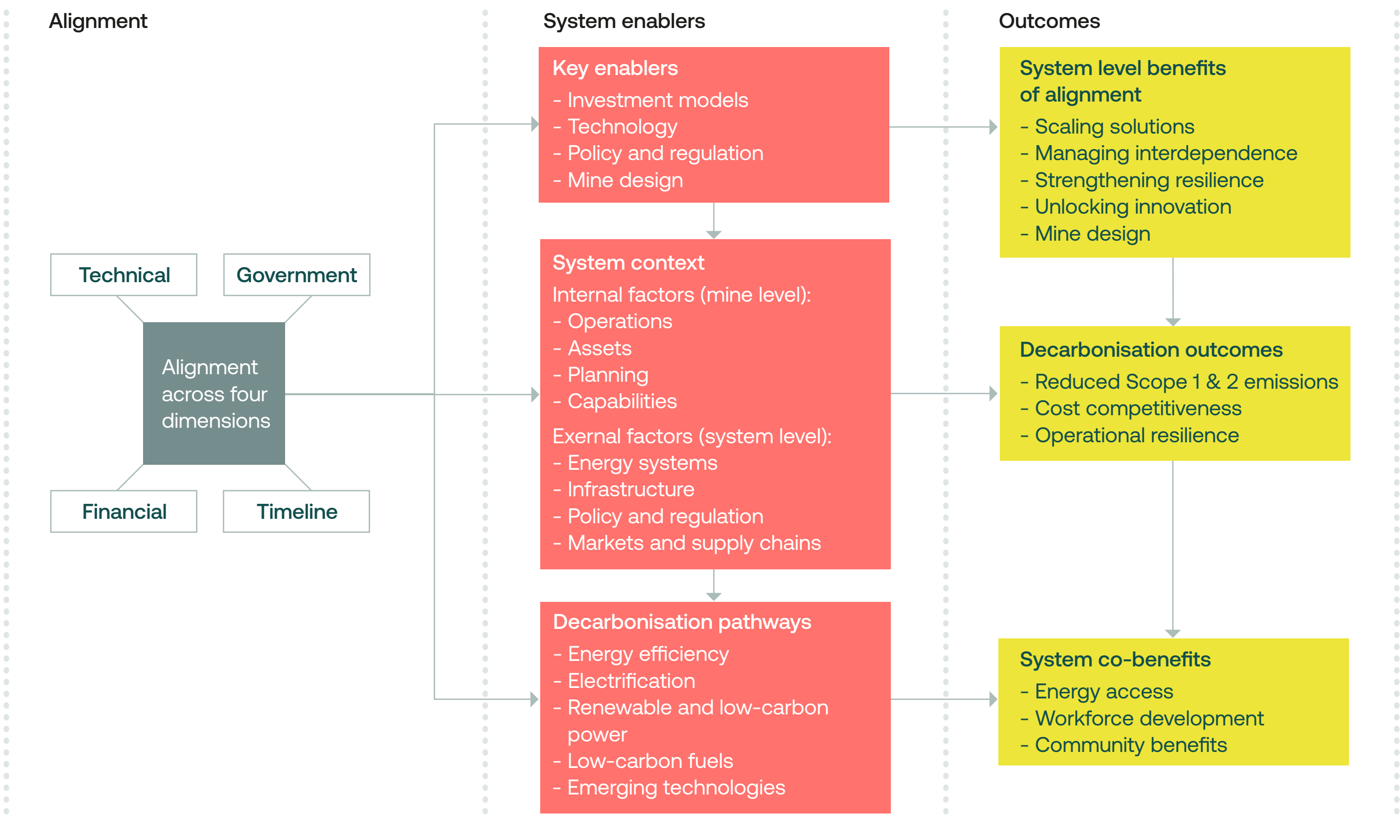
— **Governance alignment:** providing regulatory clarity, consistent standards and coordinated planning processes that reduce risk and enable delivery.

— **Timeline alignment:** synchronising asset lifecycles, infrastructure development, policy windows and workforce transitions to avoid delay and stranded investment.

Further details on how these alignment dimensions interact with internal and external system factors are provided below and in Annex 2. To bring these elements together, Figure 2 presents an integrated view of how key enablers, system-level conditions and decarbonisation pathways are connected, and how alignment across technical, financial, governance and timeline dimensions enables these elements to work together to deliver both operational outcomes and broader system-level benefits.

This integrated perspective reinforces the importance of coordination across systems, stakeholders and time horizons to enable decarbonisation at scale. In practice, alignment helps embed decarbonisation into core operational planning, capital allocation and asset management decisions. It operates both horizontally and vertically, linking actors across sectors such as mining, energy, finance and government, while also connecting corporate strategy with site-level implementation. For further background on alignment please see Annex 2.

Figure 2: Integrated Framework for Mine Decarbonisation



Translating Enabling Conditions into Implementation

10

Analysis of current initiatives and emerging best practices suggests that progress is already unfolding across three overlapping time horizons – immediate (now to 2030), medium term (2030-2035 and long term (beyond 2035). In the near term, the focus is on reducing uncertainty and accelerating early deployment through standardised planning tools, pilot collaborations and more efficient permitting processes for low-carbon energy and enabling infrastructure, while maintaining robust environmental and social safeguards. Over the medium term, attention shifts to scaling investment models, building workforce capability and embedding renewable energy into core mining operations.[39] In the longer term, the objective is full integration of mining into regional energy ecosystems and the widespread deployment of modular, autonomous and circular technologies.

The implementation roadmap below summarises priority actions across these three time horizons, highlighting where coordinated action among key stakeholders can unlock the greatest progress.

Together, these priorities provide a practical framework for translating enabling conditions into coordinated, system-wide action. While implementation will vary across regions and commodities, the roadmap highlights where collaboration can accelerate deployment and reduce investment risk.

Table 2. Priority Actions Across Immediate, Medium and Long-Term Time Horizons

Priority Action	Key Contribution	Key Stakeholders
Immediate priorities (now to 2030)		
Address cultural and structural gaps within mining organisations, and harmonise cooperation principles and blueprints	Implement integrated lifecycle performance metrics	Mining companies
	Establish 'energy literacy' competency frameworks	Mining companies, academic institutions
	Formalise cross-functional transition teams	Mining companies
	Mandate ecosystem-conscious/transition-ready modular mine design	Mining companies, governments, OEMs
	Enable cross-sector and intercompany learning and harmonised practices	Industry bodies
Deploy standardised energy-planning tools, total cost of ownership (TCO) and total cost of energy (TCE) templates to guide decision-making	Integrate TCO into investment assessments	Mining companies, financiers
	Embed tools into approval or planning requirements	Governments
	Develop or endorse common templates; provide technical assistance	Multilateral institutions
	Primary users; apply tools to operational planning	Mining companies
	Provide technical data, equipment performance and cost inputs	OEMs

39. ICMM's Innovation for Cleaner, Safer Vehicles initiative has developed a Maturity Framework, with the input of company members and OEM partners, to guide decarbonisation readiness decisions at site level. The framework supports practitioners to assess multiple dimensions across three pillars (Strategic Direction and Planning, Technical and Operational Readiness and Organisational and Safety Considerations) and accounts for the enabling factors 'outside the mine'.

Priority Action	Key Contribution	Key Stakeholders
Initiate pre-competitive collaboration forums for technology trials and operational learning	Participate in replicable integrated trials within regional blueprints	Energy providers, mining companies, OEMs
	Co-fund or observe trials to de-risk technology	Financiers
	Support enabling conditions, regulatory sandboxes	Governments
	Convene and coordinate collaboration	
	Develop standardised contractual templates appropriate to the technology and risk-sharing application that are pre-vetted by major regional financiers and intended deployment partners	Industry bodies, mining companies, OEMs, multilateral institutions, others
	Establish antitrust and legal frameworks, and data pooling and sharing mechanisms	Industry bodies and mining companies
Increase partnerships between mines, energy providers, financiers and communities to demonstrate integrated solutions	Engage in codesign and contribute as co-investors in infrastructure through benefit-sharing	Communities
	Pursue transition readiness with modular and 'grid-ready' energy-system designs for new projects	Energy providers, mining companies
	Include 'performance guarantees' and 'modular retrofitting' kits for legacy fleets	Energy providers, OEMs
	Design context-fit replicable structured finance, which could include blended finance and guarantees	Financiers, governments, others
	Facilitate permitting and grid access for low-carbon energy and enabling infrastructure	Governments
	Technical support for community benefit frameworks	Multilateral institutions
Establish regional investment platforms to mobilise blended finance and reduce risk for shared infrastructure	Infrastructure partners	Energy providers
	Development banks, private capital, blended finance providers	Financiers
	Policy direction, co-investment, guarantees	Governments
	Platform design, governance, concessional capital	Multilateral institutions
	Anchor investors or offtakers	Mining companies
Accelerate permitting processes for low-carbon energy and enabling infrastructure in priority jurisdictions, while maintaining robust environmental and social safeguards	Lead permitting improvements for low-carbon energy and enabling infrastructure, ensuring efficiency while maintaining environmental and social safeguards	Governments
	Technical support, best-practice guidance	Multilateral institutions
	Provide data to support reform	Mining companies
	Participate in improved engagement processes	Communities
	Support permitting processes for shared low-carbon energy infrastructure	Energy providers
Medium-term priorities (2030–35)		
Embed renewables into core mining operations through OpEx-based and service models	Adopt OpEx models	Mining companies
	Deliver PPAs, build, manage and operate systems	Energy providers
	Structure service-based finance	Financiers
	Support integration, interoperability with equipment fleets	OEMs
	Provide tariff clarity and regulatory support	Governments

Priority Action	Key Contribution	Key Stakeholders
Scale academic and vocational partnerships and workforce development programmes across companies and government agencies to build technical capacity	Establish energy and transition literacy programmes and regional academic curricula to grow talent pool across the economic corridor	Mining companies, governments, academic institutions
	Fund and operate training programmes	Governments
	Support vocational training needs	Mining companies
	Provide technical training for equipment	OEMs
	Support capacity building	Multilateral institutions
	Cross-sector skills development	Energy providers
Fully align mining with national climate strategies, including Nationally Determined Contribution (NDC) integration and mandatory energy transition plans	Integrate mining into national strategies, NDCs and planning	Governments
	Align corporate transition plans	Mining companies
	Policy support and climate governance	Multilateral institutions
	Align investments with transition-aligned plans	Financiers
Operationalise sector coupling and multi-modal corridor synchronisation, linking mining with other industries and regional energy systems	Coordinate and strengthen energy systems, transport infrastructure and land-use planning	Governments, mining companies, others
	Align mining energy hubs with electrified rail and logistics corridor development, as well as other industrial development priorities and anchor loads	Governments, mining companies, multilateral institutions, OEMs
	Finance shared infrastructure	Financiers, multilateral institutions, governments, mining companies
	Support regional coordination	Multilateral institutions
Implement traceability systems and responsible mining certifications at scale	Data provision and compliance	Mining companies
	Regulations, certification frameworks	Governments
	Standard-setting and verification support	Multilateral institutions
	Link finance terms to compliance	Financiers
	Supply-chain transparency requirements	OEMs
Long-term priorities (beyond 2035)		
Achieve full integration of mining into regional energy ecosystems, acting as anchor loads for renewable generation	Regional energy planning	Governments
	Anchor loads and co-investors	Mining companies
	Grid operators and generators	Energy providers
	Large-scale capital	Financiers
	Regional coordination	Multilateral institutions
	Co-benefit recipients	Communities
Mainstream circular mining models, including recycling ('urban mining') and modular design	Adopt circular models and invest in recycling	Mining companies
	Continue to design for repair, reuse and recyclability	OEMs
	Policy incentives for circularity	Governments
	Guidance and capacity building	Multilateral institutions
	Beneficiaries of repurposed assets	Communities
Scale autonomous, modular, redeployable technologies across the sector	Adopt and integrate technologies	Mining companies
	Design and supply systems	OEMs
	Support modular infrastructure	Energy providers
	Support multisite procurement models	Financiers
	Standards and approval pathways	Governments

Stakeholder Roles and Actions

11

Delivering decarbonisation at scale in the mining and metals sector requires coordinated action across the entire mining and energy ecosystem. Different actors play complementary roles in enabling the deployment of low-emissions technologies, mobilising capital, strengthening policy frameworks and building the infrastructure required for large-scale decarbonisation.

No single stakeholder can deliver the transition in isolation. Achieving alignment across technical, financial, governance and timeline dimensions depend on effective collaboration between public and private actors, as well as across sectors.

The following section summarises the principal roles and delivery mechanisms associated with each stakeholder group.

Principal roles and delivery mechanisms

Mining companies
Mining companies need to engage in policy consultation, committing to alignment with national climate goals through industry coalitions and direct government engagement. Commitment to anchor load agreements is key, as well as co-investing in shared infrastructure. In the long term, offtake agreements and sector-coupling partnerships would be effective in supporting this.

Adopting OpEx models, participating in co-investment platforms and sharing infrastructure through procurement reform and partnership agreements are also significant, as well as demonstrating accountability through credible ESG disclosure and engaging communities meaningfully, using reporting frameworks and third-party verification. Finally, participation in pre-competitive collaboration and the sharing of operational learnings through industry consortia and shared platforms would be beneficial.

Governments
Governments need to implement the embedding of mining into national climate strategies, specifically, mandating energy transition plans in project approvals with the creation of policy directives, legal reform and cabinet-level coordination. They should instigate reform of permitting processes for low-carbon energy, enabling infrastructure and private grid investment, and coordinating regional infrastructure. This can be achieved through legislative revision, regulatory sandboxes and infrastructure funding.

The provision of subsidies, guarantees and fiscal incentives is key, as well as co-investment in regional platforms. This would require stringent budget allocation and policy commitment.

Through regulation, licensing reform and fiscal policy, governments need to set baseline standards, enforcing compliance and offering incentives for high performers and early adopters. Training programmes and technical advisory support can build internal capacity for project evaluation and facilitate knowledge exchange.

Energy providers and OEMs

Energy providers should aim to co-develop transmission infrastructure, offering flexible contracting for remote locations through PPP frameworks and government co-investment. With long-term contracts and versatile pricing, delivery of renewable energy via PPAs is possible, as well as the offer of modular, scalable solutions. Sharing learnings on renewable integration and supporting hybrid system design through joint pilots and knowledge-sharing agreements are also of value in this context.

Meanwhile, OEMs should support standardisation and aim to design equipment that is compatible with renewable energy and low-carbon fuel constraints, in accordance with refreshed industry guidance and standards development.

They should look to offer equipment-as-a-service and leasing models, as well as sharing technology risk, utilising new commercial models and offering performance guarantees. Ensuring supply-chain transparency and putting emphasis on designing for circularity – with supplier codes and traceable technology – would create trust on each level of the process, as would the co-development of demonstrations, technological training provision and the sharing of readiness data, through partnership agreements and joint research and development.

Financiers

By making energy transition plans a condition of project finance, through multilateral pressure and ESG lending standards, financiers can bring change to the table. With structure-blended finance vehicles, the provision of sustainability-linked products and the reduction of risk premiums for green assets through Development Finance Institution coordination, government guarantees and green taxonomies, financiers can play a vital part in the wider context.

With ESG screening and sustainability-linked finance, non-compliant operators can be excluded from capital, with responsible mining rewarded with better terms. Financiers can also support shared infrastructure pilots and fund capacity-building initiatives by offering concessional capital and technical assistance.

Multilateral institutions

Multilateral institutions can provide technical assistance for policy development and facilitate regional coordination through partnerships and capacity-building programmes. They can assist with regulatory reform and fund cross-border transmission through grant programmes and policy exchange platforms, as well as catalysing blended finance vehicles, and providing concessional capital and technical assistance on business models through fund capitalisation and partnership brokering.

Communities

Finally, communities can play a vital role in decarbonisation by participating in regional energy-planning processes and advocating for equitable energy access through structured consultation mechanisms, as well as ensuring engagement in transparent dialogue, building trust through co-design processes and using grievance mechanisms to ensure structured engagement and capacity support.

What Next?

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Delivering a just and effective energy transition in mining depends on more than the availability of technologies or financial mechanisms. The success of decarbonisation efforts is shaped by contextual factors that determine what is feasible, the pace at which change can occur, and how risks and benefits are distributed. Regional conditions, commodity characteristics and demand, trade dynamics and energy-system configurations all influence how alignment is achieved in practice.

These factors vary significantly by geography and market, meaning that approaches effective in one context may be impractical or ineffective in another. Recognising these differences from the outset is essential to translating ambition into credible and deliverable transition pathways.

Taken together, these contextual differences have direct implications for decarbonisation strategies and investment decisions. Mining companies cannot rely on uniform pathways or standard timelines but need to prioritise flexibility, sequence investments in line with regional system readiness, and align capital deployment with policy signals, commodity demand trajectories and energy-system constraints. Strategies that are grounded in local context are better positioned to attract investment, manage risk and deliver shared benefits for surrounding communities and energy systems. By anchoring action in these realities, the enablers outlined in this report can support transition pathways that are technically viable, resilient, scalable and capable of delivering long-term value across diverse operating environments.

Looking to the future

The conditions for successful mine site decarbonisation are increasingly falling into place. Technologies are maturing, viable commercial models are emerging, and collaboration across the sector is strengthening. The challenge is no longer whether decarbonisation is possible, but how quickly it can be delivered at scale.

Over the next five years, progress will hinge on a small number of high-impact actions that align energy planning, capital mobilisation and technology deployment across sites, regions and value chains. These actions focus on integrating energy and cost planning, scaling investment through service-based delivery models, and strengthening pre-competitive collaboration to reduce technology risk and accelerate learning across the sector.

Five priorities for the next five years

Accelerating progress will require focused action across the following priorities, which together offer the greatest potential impact in the near to medium term:

1. **Embedding integrated energy and cost planning as standard practice**
   Mining companies, financiers and governments should adopt common energy-planning tools and TCO approaches to guide investment decisions. This creates a shared evidence base for comparing electrification, renewables, low-carbon fuels and efficiency measures, and reduces uncertainty for investors.
2. **Scaling deployment through service-based and shared infrastructure models**
   Wider use of PPAs, EaaS models and shared infrastructure arrangements can reduce upfront capital requirements and accelerate deployment, particularly where mine assets have shorter lifecycles or grids are constrained.
3. **Accelerating pre-competitive collaboration to de-risk technology adoption**
   Joint trials, shared standards and coordinated learning are essential to move solutions from pilots to deployment. Collaboration between mining companies, OEMs, energy providers and regulators can shorten learning curves and reduce duplication.
4. **Strengthening workforce capability and operational readiness**
   Decarbonisation at scale requires skilled operators, engineers and regulators. Coordinated workforce development across companies and regions is needed to support electrification, renewable integration and new operating models.
5. **Mainstreaming circular design and closed-loop practices**
   Circular approaches should be treated as a core efficiency lever, with circularity across key materials offering the potential to reduce emissions by up to 40% by 2050. At the mine site level, this includes designing for refurbishment and upgrade, increasing reuse of components and integrating recycling and material recovery to lower energy demand, reduce costs and enhance resilience.

From priorities to delivery

Delivering sustained progress against the five priority areas requires coordinated action from each of the key groups of stakeholders across the ecosystem. Mining companies must adopt proven models and participate in partnerships that enable scale. Energy providers need to deliver modular, reliable and integrated solutions. Financiers must continue to innovate in structuring capital and sharing risk. Governments play a central role in providing policy certainty, regulatory alignment and efficient permitting for low-carbon energy and enabling infrastructure. OEMs are critical to ensuring technology readiness, interoperability and circular design. Communities and multilateral institutions help shape outcomes, build capacity and ensure benefits are shared.

ICMM also has a distinctive role to play, as a convenor of key stakeholders across the enabling ecosystem and a catalyst for collective action. In the near term, ICMM will focus on areas where coordinated leadership can unlock progress that no single organisation can achieve alone – supporting pre-competitive collaboration, developing shared tools and frameworks, engaging policymakers and multilateral institutions, and improving transparency and accountability across the sector. In this way, fragmentation can be reduced, investor and regulator confidence strengthened, and the transition from ambition to delivery accelerated.

An urgent call to action

The window for decisive action is narrowing. Demand for minerals is rising, competition for clean energy is intensifying and infrastructure constraints are becoming more pronounced. Mining can be an effective cornerstone of the global energy transition, but only if alignment is translated into delivery now.

Mining has the potential not only to support the energy transition but to accelerate it. By aligning internal capabilities with external systems across technical, financial, governance and timeline dimensions – supported by the enabling conditions described in this report, the sector can unlock rapid, large-scale decarbonisation and resilient, low-carbon economic development.

The priorities outlined above are the foundation of an implementation roadmap where focused leadership and collaboration over the next five years can unlock the greatest impact. ICMM calls on its members and partners to focus on these priorities, collaborate across boundaries and accelerate the transition from ambition to delivery. With sustained collaboration and decisive action, the sector can accelerate decarbonisation while strengthening resilience, maintaining competitiveness and delivering longterm value for economies, communities and the energy systems that depend on its products.

Annex 1: Glossary of Key Terms

Table 3. Glossary of Key Terms

Term	Definition
Alignment	The synchronisation of decisions, systems and incentives across technical, financial, governance and timeline dimensions to enable scalable decarbonisation delivery.
Anchor load	A large, stable energy user (such as a mine) that can support investment in generation and network upgrades by providing longterm demand certainty.
Blended finance	The use of concessional and commercial capital together to improve project viability and reduce risk for private investment.
Circularity	Circular design and operating practices such as refurbishment, reuse, recycling and material recovery that reduce energy demand and resource dependency over time.
Closed-loop systems	Circular approaches that keep materials and components in use through reuse, refurbishment, recycling and recovery, reducing waste and lowering reliance on primary inputs.
Concessional finance	Finance provided on terms more generous than market rates (for example, lower interest or longer tenors) to reduce cost and risk in priority projects.
Decarbonisation pathways	The main practical approaches available to reduce operational emissions, including energy efficiency, electrification, renewable and low-carbon power integration, low-carbon fuels and emerging technologies.
Electrification	Replacing fossil-fuelled mobile or stationary equipment with electric alternatives, supported by charging infrastructure and adequate power supply.
Emerging technologies	New or fast-maturing technologies and operating models that require structured trials, learning and governance to move from pilots to scaled deployment.
Energy-as-a-service (EaaS)	A service-based commercial model where energy infrastructure and services are provided under contract, supporting deployment without large upfront capital outlay.
Energy efficiency and demand reduction	Operational and technical measures that reduce total energy use, lowering baseline demand and improving the economics of electrification and clean power supply.
Financial alignment	Coherence between internal capital allocation and budgeting decisions, and the external financial environment, including cost structures, risk-sharing and financing approaches that enable low-carbon investment.
Governance alignment	Coherence across governance arrangements, regulatory frameworks, stakeholder relationships and planning processes that shape how decarbonisation is prioritised, enabled and delivered.
Hybrid system	An energy system combining two or more generation or storage types (for example, solar plus batteries and backup generation) to improve reliability and emissions performance.
Interoperability	The ability of different technologies, equipment and systems to work together effectively, supported by standards and compatible interfaces.
Low-carbon liquid fuels	Transitional fuels such as biodiesel or renewable diesel used where electrification is not yet feasible, requiring alignment with fuel standards, certification and supply chains.
Key enablers	The four enabling conditions highlighted in prior ICMM work and retained in this report: technological innovation and deployment; mine design and next-generation thinking; innovative investment models; supportive policies, regulations and international agreements.
Microgrid	A local energy system that can operate independently or with the grid, often used for remote sites or to improve reliability and enable renewables integration.
Modularity	Designing systems in standardised units that can be deployed in stages, expanded, upgraded or redeployed to manage risk and adapt to changing site needs.

Term	Definition
Power Purchase Agreement (PPA)	A longterm contract for electricity supply that can enable renewable procurement and support service-based delivery models.
Renewable and low-carbon power integration	Supplying mine operations with low-emissions electricity through grid procurement, on-site generation, storage and hybrid systems, tailored to local grid and permitting conditions.
Regulatory sandbox	A controlled regulatory environment that allows testing of new business models or technologies while rules evolve and risks are managed.
Sector coupling	Linking mining energy demand and infrastructure with other large loads or systems, such as data centres and regional grids, to enable shared investment and system efficiency.
Technical alignment	Coherence across physical systems, technologies, equipment and infrastructure so they operate as an integrated system, including interoperability, modularity and integration with external energy networks and fuel supply systems.
Timeline alignment	Synchronisation of planning horizons, investment cycles, asset lifecycles and policy timelines to support coherent and timely decarbonisation outcomes.
Total cost of energy (TCE)	A cost approach referenced alongside TCO to support business cases for lower-carbon power, factoring the cost of supplying energy over time.
Total cost of ownership (TCO)	A whole-of-life cost approach used to compare technology and investment options, including capital, operating costs and other lifecycle factors.
Traceability	Systems that track the origin and attributes of materials through supply chains, supporting verification of responsible and low-emissions production.

Annex 2: System Alignment Ecosystems

Technical alignment

Technical alignment refers to the coherence across the physical systems, technologies, equipment and infrastructure required to decarbonise mining operations. It involves ensuring that energy systems, mobile and stationary equipment, digital tools and supporting infrastructure operate as a coordinated system rather than as isolated components. Essential qualities include interoperability between technologies, compatibility with both legacy and emerging systems, resilience in demanding mining environments, modularity that supports phased deployment, and the ability to integrate with external energy networks and fuel supply systems.

Technical alignment is the foundation that allows decarbonisation solutions to function reliably and at scale. Without it, financial mechanisms, policy support or individual technologies cannot deliver their intended impact. This is particularly important as sites combine multiple decarbonisation pathways – including fleet electrification, renewable energy, low-carbon fuels and digital optimisation – within constrained energy systems. See table 4 for more details.

Key enabler impacts

Technical alignment strengthens each key enabler by ensuring that investments, policies and design choices translate into operable outcomes. Innovative investment models depend on technologies that can be integrated

into service-based or third-party ownership structures, such as PPAs or fuel supply contracts. Technology deployment relies on infrastructure and standards that support safe operation, interoperability and replication across sites. Policy and regulatory frameworks reinforce technical alignment through safety standards, grid codes, fuel specifications and interoperability requirements. Mine design benefits when technical alignment is considered early, reducing retrofit costs and enabling flexibility as technologies evolve.

There is increasing pressure on grid infrastructure and critical equipment, including transformers and switchgear, as electricity demand accelerates across sectors.[40] These constraints reinforce the importance of selecting technologies that can operate under variable grid conditions, integrate storage or hybrid solutions, and adapt to evolving external infrastructure availability.

Alignment across internal and external systems
Internal systems must function in a coherent and complementary manner. Electrified fleets need to align with on-site charging infrastructure, operational schedules and maintenance regimes. For renewable energy systems to sustain reliability and efficiency, they must be matched to site load profiles and supported by appropriate storage or firming solutions. Digital tools, including automation and fleet optimisation systems, must align with workforce capability, data architecture and operational decision-making processes.

Low-carbon liquid fuels also require technical alignment. Fuel compatibility with engines, storage systems and handling procedures must align with external fuel standards, supply chains and regulatory requirements. Where fuels are used as transitional solutions, technical choices should avoid locking in equipment or infrastructure that constrains future electrification.

Technical alignment must also extend beyond the site boundary. Electrification depends on external grid capacity or reliable microgrid solutions. Renewable energy deployment depends on external permitting processes, grid connection requirements and access to network services.

Circularity practices provide an important, and often under-recognised, contribution to addressing these challenges. At the site level, circular design approaches – such as refurbishing and upgrading equipment rather than full replacement, improving component reuse and optimising material flows – can reduce energy demand and emissions intensity. Over time, greater use of recycled materials and closed-loop systems reduces the energy required for primary extraction and processing, reinforcing decarbonisation efforts across Scope 1 and Scope 2 activities.

Circularity initiatives depend on the availability of external recycling markets and compliant logistics systems. System-level energy planning, modular renewable solutions and collaborative technology development all illustrate how internal and external components must be synchronised.

Case Studies

- The B2Gold Fekola Mine in Mali demonstrates strong technical alignment through a modular solar and battery system that supplies up to 75% of daytime power. The ability to expand or relocate the system shows how modularity reduces risk and enables energy systems to evolve alongside mine operations.
- Boliden's circularity approach illustrates how internal processing technology can align with external recycling markets. By processing 330,000 tonnes of secondary material in 2023, Boliden demonstrates how technical readiness can support circularity at scale.
- The Envusa Energy partnership in South Africa shows technical alignment at a regional level. By co-developer 3–5 GWs of renewable capacity, mining and energy actors align mine electrification needs with broader grid development and energy-system planning.

40. Energy Investors Capitalize on Soaring Power Demand | Reuters Events

Table 4. Technical Alignment Ecosystem

Internal Factors	External Factors	Barriers	Mitigation	Outcome
Electrification of fleets and equipment	Access to reliable, sustainable, affordable, low-emissions power, and quantities of electric fleets and equipment	Weak or constrained grids, high CAPEX required for transmission infrastructure and for microgrids, commercially ready BEVs, HEVs for large surface haulage	Infrastructure-first planning for sequenced electrification and flexible charging strategies aligned with operational cycles and load profiles as BEV haulage matures	With enough electrified vehicles and low-cost electricity available, energy costs can reduce by 40-70%[41], reducing dependence on diesel and enabling scalable, emissions reduction pathways
Renewable energy systems and storage	Permitting regimes, interconnection processes and grid services	Delays and inconsistent requirements for permitting and grid connection create technical and commercial uncertainty	Use of modular and standardised system designs, investment in microgrids or staged grid upgrades combined with early engagement with regulators and network operators to align technical requirements	Renewable systems can be deployed and expanded in phases, lowering power-related emissions while maintaining continuity of operations
Digital systems, automation and fleet management	Interoperability, standards, data governance and safety frameworks	Fragmented standards and limited supplier compatibility slow system integration and increase operational complexity	Adoption of open standards, early specification of interoperability requirements, and phased integration across digital and operational systems	Optimised operations reduce energy use, improve equipment utilisation, and support continuous efficiency gains across the site
Transition of legacy equipment and technologies	Supply chains for modern technology and equipment components for retrofitting, upgrades and maintenance	Legacy equipment and scarcity of components limit integration and constrain performance improvements	Targeted retrofitting programmes, longterm procurement planning, and alignment of efficiency upgrades with maintenance and replacement cycles	Lower baseline energy demand reduces overall energy intensity and improves resilience to energy price volatility and supply disruptions
Low-carbon liquid fuel systems	Fuel standards, certification schemes and supply chains	Adoption constrained by inconsistent fuel specifications, regulation lagging technical advancement, limited feedstock availability, and uncertainty over longterm supply	Alignment with recognised fuel standards, early engagement with suppliers, and design of fuel systems that avoid lock-in and support future electrification	Near-term emissions reductions are achieved where electrification is not yet feasible, while preserving flexibility for future transition pathways
Circularity technologies	Material recovery supply chain, secondary material markets and regulatory frameworks	Fragmented recycling ecosystems and jurisdictions with no recycling legislation reduce the viability of circular solutions	Longterm offtake agreements with e-waste supply chains, development of processing capacity, and effective legislation to increase capture of resources from waste streams	Use of recycled materials with primary ores can lower embedded energy use, decreases overall energy intensity, and strengthen supply chain resilience

41. Actual results will depend on site-specific factors like power prices and mine design. Mining electrification could double their electricity demand | McKinsey

Financial alignment

Financial alignment refers to the coherence between internal capital allocation and budgeting decisions and the external financial environment that enables and supports decarbonisation. It requires costs, risk profiles, investment timelines and asset lifecycles to be compatible with available financial structures. Core qualities include affordability, flexibility, transparent pricing, predictable cost recovery and risk-sharing arrangements that encourage investment in low-carbon solutions.

Recent market signals reinforce the importance of financial alignment. This is highlighted by strong investor confidence in the energy transition, with a majority of private-market investors across regions viewing the transition as irreversible and reporting accelerating investment activity. At the same time, investors continue to seek projects with clear revenue structures, longterm contracting and manageable policy risk. Large-scale capital mobilisation is already under way, illustrated by the launch of multi-billion-dollar dedicated energy transition funds and increased investment in renewables, grids, storage and enabling infrastructure. These trends underline the opportunity for mining companies to position decarbonisation projects in ways that align with prevailing investor expectations for scale, durability and risk management.

In a context of rising capital costs and increasing competition for transition finance, projects that fail to demonstrate financial alignment risk delayed approval or higher cost of capital. See table 5 for more details.

Key enabler impacts

Financial alignment is central to innovative investment models, as it enables leasing, EaaS models and shared infrastructure arrangements. It supports technology deployment by making early-stage or capital-intensive technologies financially feasible. Supportive policies amplify financial alignment through incentives that improve the business case. Financial alignment is beneficial for mine design because early-stage choices reduce lifecycle costs and improve bankability.

The Soaring Power Demand report provides a useful illustration of how complex financing stacks are being assembled for clean power projects.[42] Typical solar and storage developments increasingly combine senior debt, tax equity or incentive-linked capital, mezzanine finance and long-term offtake agreements under PPAs. This layered approach spreads risk, lowers the cost of capital and attracts diverse investor pools. For mining companies, similar structures can be applied to on-site or co-located renewable energy projects, provided internal financial models and procurement processes are aligned with long-term contracting and financing requirements.

For mining companies, replicating such layered financing structures requires internal procurement and accounting systems that can accommodate long-term contractual complexity.

Alignment across capital structures and market mechanisms

Internal financial models must support multiyear decarbonisation plans rather than single-year budget cycles. The balance between OpEx and CapEx must align with operational needs, especially when adopting service-based models. Mine-life forecasts must match the expected lifetime of major energy assets. Procurement processes must align with longterm contracting structures like PPAs.

External financial mechanisms must also align with internal strategies. Access to concessional and blended finance, as well as guarantees, needs to match corporate capital strategies and risk tolerance. Revenue structures under PPAs must remain consistent with regulated tariff frameworks. Financing windows need to align with project sequencing, permitting and grid connection timelines. When internal financial planning is coordinated with external financial tools and market conditions, investment risk declines and viable decarbonisation projects can progress at scale.

Case Studies

- The Bolobedu Solar Consortium in South Africa demonstrates how shared ownership and a longterm PPA reduce financial risk. Community ownership elements also enhance social value.
- Envusa Energy integrates capital from mining and renewable developers to cofinance large-scale infrastructure, aligning internal cost structures with regional energy-system development.

42. Energy Investors Capitalize on Soaring Power Demand | Reuters Events

Table 5. Financial Alignment Ecosystem

Internal Factors	External Factors	Barriers	Mitigation	Benefits
Capital budgets for electrification and renewables	Blended finance and concessional capital availability	Mismatched lifecycles between mines and energy assets can hinder financing due to unfavourable ROI	Use of shared-ownership structures, special-purpose vehicles and flexible contracting to align asset and mine lifespans.	Reduced capital barriers enable faster deployment of clean technologies.
OPEX and CAPEX strategies	Tariff structures, tax incentives and duties	Tariff uncertainty and volatile policies erode investor confidence.	Early engagement with regulators, longterm tariff agreements and structuring investments to maximise available incentives.	More predictable cost structures improve investment certainty and support longterm planning.
Mine life planning	Investor return horizons and asset lifecycles	Fragmented financing mandates and limited access to concessional capital.	Aggregated demand across sites, co-investment platforms and multi-asset financing arrangements.	Shared ownership models reduce risk and improve project viability.
Procurement models and contract structures	Financing platforms and regulatory compliance requirements	High upfront costs for emerging technologies.	Adoption of service-based models, performance-linked payments and procurement frameworks that de-risk early adoption.	Improved bankability of decarbonisation projects.
Risk tolerance and investment horizon	Market signals, subsidies and carbon pricing	Weak or inconsistent market signals slow investment in low-emissions solutions.	Integration of internal carbon pricing, scenario planning and portfolio-level risk management.	Stronger and more predictable investment signals accelerate capital allocation to transition-aligned projects.

Governance alignment

Governance alignment refers to coherence across internal governance arrangements, regulatory frameworks, stakeholder relationships and planning processes that shape how decarbonisation is prioritised, enabled and delivered over time. It depends on clear direction, coordinated decision-making, inclusive engagement and regulatory systems that support longterm transition objectives. Essential qualities include predictability, clarity, transparency and the capacity to coordinate across agencies, partners and communities.

Recent developments in global energy markets underscore the growing importance of governance alignment. Geopolitical tensions, energy security concerns and shifting trade policies are reshaping supply chains and regulatory priorities.[43] Governments are increasingly promoting domestic manufacturing and onshoring of critical energy infrastructure, including transformers, inverters and grid equipment, often supported by tariffs and trade measures. While these trends can strengthen supply-chain resilience, they can also introduce cost pressures, longer lead times and interoperability challenges if standards and procurement strategies are not aligned. See table 6 for more details.

Key enabler impacts

Governance alignment reinforces innovative investment models by providing stable and transparent rules for third-party power ownership, permitting for low-carbon energy and enabling infrastructure, and grid access. Technology deployment relies on consistent standards, clear approval pathways and regulatory certainty. Policy frameworks act as instruments of governance alignment by guiding markets and enabling collaboration across sectors. Mine design depends on governance systems that align permitting processes for energy and infrastructure, land use planning and stakeholder engagement from the earliest stages of development.

Demand for grid equipment has increased sharply, with tariffs and onshoring policies accelerating domestic manufacturing investment in some regions.[44] These dynamics reinforce the importance of early procurement planning and interoperability standards, particularly for equipment such as transformers and switchgear, which face long lead times. Governance systems that support standardisation and cross-border compatibility can reduce delivery risk and avoid lock-in to proprietary or region-specific solutions.

43. Harnessing renewables in Sub-Saharan Africa: Barriers, reforms and economic prospects | International Monetary Fund
44. Energy Investors Capitalize on Soaring Power Demand | Reuters Events

Alignment across regulatory and institutional systems
ESG commitments need to be embedded in operational practice and investment decisions. Community engagement should be integrated into project planning from the outset. Internal teams must understand regulatory requirements and work in a coordinated manner to meet them.

Externally, governance alignment requires synchronisation between corporate strategies and regulatory expectations. Electrification projects must align with permitting systems for charging infrastructure and grid upgrades. Renewable energy developments need to reflect national climate priorities and regional land-use plans. Regulatory sandboxes can support the testing of new technologies and business models where rules are evolving. Labour and skills planning should align with national training programmes and cross-sector workforce needs. In a context of evolving trade and industrial policy, early engagement with regulators and suppliers is increasingly important to manage procurement risk, ensure interoperability and maintain project timelines.

Case Studies

- Chile's integrated mining–energy planning shows how coordinated policy and infrastructure planning can reduce delays and improve certainty for both operators and investors.
- The Weipa Solar Farm in Australia demonstrates how institutional alignment supports shared energy solutions. By supplying power to both the mine and the local community, the project reflects early engagement, appropriate permitting and coordinated planning.
- The Mpatamanga Hydro Project in Malawi demonstrates how coordinated public-private partnerships can mobilise large-scale clean-energy infrastructure, by bringing together the IFC, World Bank, EDF, Scatec and the government of Malawi to advance the country's clean-energy transition.

Table 6. Governance Alignment Ecosystem

Internal Factors	External Factors	Barriers	Mitigation	Benefits
Governance systems and decision making	Permitting frameworks and regulatory processes	Fragmented regulation delays projects and increases risk.	Participation in policy consultation, alignment of internal processes with regulatory expectations and early engagement with permitting authorities.	Predictable regulatory environments encourage investment.
ESG commitments and transition strategies	National climate strategies and international commitments	Slow and inconsistent permitting creates uncertainty.	Integration of transition plans into permitting submissions, use of clear disclosure frameworks and alignment with national climate pathways.	Faster permitting enables quicker project delivery.
Workforce planning	Skills development programmes and labour market factors	Weak and unclear transition planning misaligned to decarbonisation timelines undermine accountability and trust.	Investment in governance, transparent reporting and partnerships with training institutions.	A more resilient, confident workforce and stronger social licence through meaningful engagement.
Community engagement processes	Land use planning, water rights and social licence mechanisms	Limited governance capacity in some jurisdictions.	Development of structured engagement processes, capacity-building for local stakeholders and shared decision-making mechanisms.	Clear governance improves coordination across actors.

Timeline alignment

Timeline alignment refers to the synchronisation of planning horizons, investment cycles, asset lifecycles and policy timelines to support coherent and timely decarbonisation outcomes. It requires foresight, flexibility and the ability to sequence projects so that key milestones reinforce rather than delay one another. Essential qualities include long-term stability, clear sequencing, upgradability and the ability to avoid stranded assets.

Timeline alignment is increasingly important in the context of rising power demand and infrastructure constraints. Surging demand across sectors and ageing infrastructure in some regions drives longer lead times for grid upgrades and critical equipment.[45] These dynamics increase the risk of misalignment between site-level decarbonisation plans and external system readiness.

As infrastructure lead times extend and technology supply chains tighten, misalignment of project sequencing can materially increase cost and delay delivery. See table 7 for more details.

Key enabler impacts

Timeline alignment strengthens innovative investment models by matching financing horizons to asset lifecycles and contractual arrangements. It supports technology deployment by ensuring that technologies are adopted when they are sufficiently mature and supported by enabling programmes consistent with project development timelines. Mine design embeds timeline coherence by incorporating flexibility and future-readiness into early design decisions.

Alignment across planning horizons and delivery milestones

Internal decarbonisation roadmaps need to integrate fleet replacement cycles, renewable energy deployment stages and evolving energy-system requirements. Workforce transition plans must align with equipment replacement and new operational demands. Mine-life planning should anticipate changes in energy supply and identify opportunities to repurpose assets during late-life or closure phases, including for renewable generation or storage.

Externally, timeline alignment requires synchronisation with infrastructure development, permitting cycles and policy incentives. Fleet electrification depends on the timely availability of charging infrastructure and grid capacity. Renewable energy projects need to align with grid upgrade schedules or the deployment of modular, off-grid or hybrid solutions. Low-carbon fuel strategies must align with supply availability and regulatory approval processes. Closure and repurposing plans should coincide with regional energy strategies and market demand. Where timelines are aligned, delivery risk is reduced and transition pathways remain credible under changing system conditions.

Case Studies

— Fekola's modular hybrid energy system demonstrates temporal alignment. Its design enables expansion over time and supports staged decarbonisation in line with operational needs.

— Repurposing of the **Touquoy** and **Kidston mines** shows how longterm planning enables former mine sites to become renewable-energy assets, replacing extraction with energy storage and generation.

45. Harnessing renewables in Sub-Saharan Africa: Barriers, reforms and economic prospects | International Monetary Fund

Table 7. Timeline Alignment Ecosystem

Internal Factors	External Factors	Barriers	Mitigation	Benefits
Fleet replacement cycles	Grid upgrade and interconnection timelines	Short-term planning limits strategic decarbonisation.	Align fleet transition plans with grid-upgrade schedules and use interim hybrid or modular charging solutions.	Reduced retrofit costs and avoidance of stranded assets.
Decarbonisation roadmaps	National policy cycles and review periods	Policy changes may occur before project delivery.	Align project milestones with policy windows, use scenario planning and maintain flexible project pipelines.	Efficient sequencing of investments improves outcomes.
Mine life planning	Technology maturity and commercial readiness	Technology maturity uncertainty creates timing risk.	Phased adoption, technology pilots and structured decision gates linked to readiness levels.	Greater resilience during technological transitions.
Closure and repurposing planning	Financing availability windows	Variable permitting timelines disrupt coordination.	Integrate closure, repurposing and energy-transition planning early, supported by long-term agreements with regulators and financiers.	Better integration of closure and repurposing planning.
Workforce transition plans	Training programme timing and education system capacity	Misaligned training cycles delay workforce readiness.	Co-design training with providers, schedule programmes to match technology rollouts and create continuous learning pathways.	A workforce prepared for emerging technologies and smoother implementation.

Annex 3: Regional Perspectives – Barriers and Enablers Across Major Mining Regions

Macro-level factors driving mining decarbonisation appear differently across the world's major mining regions. Local contexts such as energy mix, regulatory frameworks, infrastructure maturity, social dynamics and economic conditions strongly influence which barriers or enablers dominate, and mean that approaches that succeed in one region may not be directly transferable to another.

Understanding these regional realities is essential for tailoring effective decarbonisation strategies that reflect jurisdictional complexity and operational feasibility.

This Annex explores how regional business environments shape the pace and scope of transition efforts, highlighting distinct challenges and opportunities for the mining and metals industry across diverse geographies. Rather than a single global pathway, decarbonisation in mining is characterised by region-specific combinations of constraints and opportunities:

Sub-Saharan Africa: Renewable Opportunity Meets Infrastructure Challenges

Sub-Saharan Africa holds immense potential for mine site decarbonisation, underpinned by abundant solar and wind resources. However, fragmented energy infrastructure and limited grid access continue to constrain deployment. Modular renewable systems and hybrid microgrids offer viable solutions, but roll-out is often delayed by underdeveloped transport networks, seasonal access limitations and shortages in skilled labour.

Policy and investment advisers must navigate inconsistent permitting regimes and limited integration of climate policy. PPPs and concessional finance can help reduce investment risk, especially when supported by coordinated planning across government, industry and civil society. Political and social dynamics, including governance fragility, union resistance and community displacement, require careful engagement to ensure inclusive and sustainable outcomes.

Several countries in the region, including South Africa, are positioning themselves to benefit from rising global demand for critical minerals. Africa holds over 30% of known reserves of key transition minerals such as cobalt, manganese and platinum. South Africa's Climate Change Act exemplifies efforts to align decarbonisation with economic opportunity, while regional strategies increasingly link mineral development to infrastructure investment and trade agreements. If managed strategically, the energy transition could boost sub-Saharan Africa's GDP by up to 12% over the next 25 years.[46]

RN 300 Initiative – Africa	
Stakeholders	IFC, World Bank, African Development Bank, Rockefeller Foundation
Purpose & Focus	Large-scale energy access initiative focused on transmission infrastructure and regulatory reform to enable renewable energy deployment across mining and other sectors.
Reported Outcomes	Progress in policy alignment and infrastructure planning to support decarbonisation.

> 'RN 300 initiative… connecting and providing energy access to 300 million Africans.'

Latin America: Policy Leadership and Geological Advantages

Latin America's mining sector benefits from progressive climate policies and rich deposits of transition minerals, particularly lithium and copper, with progressive climate policies. Chile[47] and Peru[48] have embedded mining into national decarbonisation strategies, enabling site operators to consider rapid adoption of electrification and renewables. Technology providers are responding with tailored solutions for diverse terrains, legacy operations and unique environments. OEMs regularly trial new technologies across the region.

Investment advisers are drawn to clear permitting pathways and fiscal incentives but must account for regulatory fragmentation. The region's strong renewable grid matrix supports clean power integration, while innovative biofuel pathways, such as second-generation ethanol in Brazil, repurpose degraded land for biofuels agriculture. Collaboration between policymakers, operators and energy providers is essential to scale innovation and ensure that decarbonisation efforts deliver both environmental and economic value.

Scatec Solar PV Lease Model (Mexico)	
Stakeholders:	Scatec, mining companies, solar PV developers
Purpose & Focus	Deployment of a 10–20 MW solar PV installation at a gold mine using a lease model to overcome capital cost barriers and reduce Scope 2 emissions.
Outcomes	A pilot installation has been completed, with further engagements under way to scale the model across other sites.

> 'We've done a 10 to 20 MW solar PV installation at a gold mine in Mexico… using a lease model to get around the CapEx hurdle.'

46. Harnessing renewables in Sub-Saharan Africa: Barriers, reforms and economic prospects | International Monetary Fund
47. Chile 2050 Energy Transition Roadmap | IEA
48. World Energy Trilemma-Peru | World Energy Council

Asia-Pacific: Diverse Progress Across Economies

Decarbonisation efforts across Asia-Pacific vary significantly. Australia is advancing with electrified fleet trials and renewable integration, while parts of Southeast Asia face persistent infrastructure gaps, limited policy coherence and uneven governance capacity. Technologies must be adapted to local conditions, including extreme heat, humidity and dust. Energy providers are developing modular systems suited to tropical and remote environments, but deployment is often constrained by seasonal access, road damage and narrow windows for infrastructure delivery.

Policy advisers require tailored strategies. Advanced economies benefit from complex financing instruments, whereas emerging markets need capacity building and workforce development. Investment models must reflect this diversity. Regional collaboration is increasingly important for accelerating progress.

In Australia, aligning government, industry and traditional custodians remains a challenge. In regions such as the Pilbara, lack of consensus has delayed shared infrastructure initiatives.

Renewable Diesel Self-Generation in Queensland	
Stakeholders	Rio Tinto, local partners
Purpose & Focus	Rio Tinto is exploring renewable diesel production using biogenic feedstock from a farm in South Burdekin, Queensland. This initiative supports the transition away from fossil diesel and complements electrification efforts.
Reported Outcomes	Strategic partnerships are being formed to assess feasibility and scalability.

> ‘We’re looking at a biogenic farm in South Burdekin to produce renewable diesel… it’s about creating a local supply chain that supports our decarbonisation goals.’

Europe: Comprehensive Decarbonisation Business Ecosystems

Europe leads in building a comprehensive decarbonisation ecosystem, combining policy ambition with multi-sector coordination. Investors and operators benefit from clear regulatory frameworks and green finance instruments that support innovation and reduce transition risk. The European Union Emissions Trading System (EU ETS) and the CBAM form the backbone of regional climate policy, driving internal emissions reductions while protecting competitiveness across borders.

Policymakers enforce stringent emissions standards and promote circular economy practices, supported by industrial decarbonisation hubs in countries such as Germany, Sweden and the Netherlands. Site operators are embedding decarbonisation into core strategy through electrification, digitalisation and automation. Technology and energy providers offer scalable solutions tailored to diverse geological and operational contexts. OEMs are increasingly integrated into regional innovation clusters, co-developing low-carbon technologies and trialling them across active mine sites.

Europe’s success lies in its ability to align stakeholder incentives, foster cross-sector partnerships and maintain transparency in climate reporting. The inclusion of free carbon allowances under the EU ETS is accelerating investment in clean technologies. The CBAM is reshaping trade flows and reinforcing the value of low carbon production.

Anglo American–EDF Partnership	
Stakeholders	Anglo American, EDF
Purpose & Focus	An innovative energy procurement model to facilitate renewable energy access for mining operations, addressing barriers such as capital cost and policy uncertainty.
Reported Outcomes	Demonstrates a replicable model for overcoming ecosystem challenges in decarbonisation.

> ‘Anglo–EDF is a great example of a new model to overcome some of these barriers.’

North America: Market and Policy Influence

In North America, shifts in federal leadership have prompted mining companies to reassess long-term decarbonisation strategies. Policy and investment advisers are navigating evolving regulatory frameworks, while site operators adjust planning in response to changing expectations around climate action. Technology providers are supporting this transition with scalable solutions for electrification and automation across diverse operational settings.

In Canada, social and labour dynamics, including union negotiations, influence the pace of technological adoption, requiring operators to balance innovation with workforce considerations. Federal climate policies and clean energy programmes are advancing mine site electrification and emissions reduction. Energy providers are delivering integrated solutions compatible with legacy infrastructure. Continued collaboration among stakeholders is essential to drive innovation and competitiveness. The mining and metals sector can also benefit from decarbonisation efforts in other industries facing similar emissions targets and policy challenges.

A unique enabler in North America is the spillover effect from decarbonisation efforts in adjacent sectors such as automotive, steel and manufacturing. The automotive industry, which consumes nearly one third of US steel output, is accelerating demand for fossil-free steel as EV production ramps up. This shift is prompting steelmakers to invest in low-emission technologies, supported by federal funding through programmes such as the Inflation Reduction Act and the Advanced Research Projects Agency–Energy. Clean industrial hubs are emerging in regions like California and Texas, where coordinated investment across sectors is catalysing shared infrastructure and innovation pipelines. Mining companies stand to benefit from these developments through access to green inputs, co-located energy solutions and policy alignment. As industrial policy converges around clean energy and critical minerals, mining is increasingly positioned not just as a participant, but as a strategic beneficiary of broader decarbonisation momentum.

Freeport's Electrification of Haul Trucks	
Stakeholders	Freeport, Caterpillar, Komatsu, Liebherr and others.
Purpose & Focus	Freeport is piloting battery-electric haul trucks at one of its mines, working closely with OEMs to gather performance data and refine electrification strategies. The initiative also explores autonomy, trolley electrification and digital-fleet management to reduce Scope 1 emissions.
Reported Outcomes	One battery-electric haul truck is currently operational. Autonomous processes are being implemented at the Bagdad mine in the US, with ongoing collaboration meetings to advance electric mobility.

'We have one battery-electric haul truck currently running in one of our mines. It is an important step in testing the future of electrified haulage.'

Reference List

Anglo American. (2021, April 15). Anglo American secures 100% renewables across South American operations [Press release]. Retrieved from https://www.angloamerican.com/media/press-releases/2021/15-04-2021

ARENA (Australian Renewable Energy Agency). (2020). Advancing renewables program: Remote microgrid projects. ARENA. https://arena.gov.au/projects/

ARENA (Australian Renewable Energy Agency). (updated 2026, April 16). Weipa 6.7MW Solar Photovoltaic (PV) Solar Farm. https://arena.gov.au/projects/

Benchmark Intelligence. (2022, September 6). More than 300 new mines required to meet battery demand by 2035. https://source.benchmarkminerals.com/article/more-than-300-new-mines-required-to-meet-battery-demand-by-2035

Cai, K., Lemaire, T., Medici, A., Melina, G., Schwerhoff, G., & Thube, S. D. (2024, October 9). Harnessing renewables in Sub-Saharan Africa: Barriers, reforms and economic prospects (IMF Staff Climate Note No. 2024/005). International Monetary Fund. https://doi.org/10.5089/9798400290107.066

CharIN. (2025, March 28). Celebrating a second year full of accomplishments in the CharIN-ICMM Project Mining. https://www.charin.global/news/mining-newsletter-2025/

Cobalt Institute. (2024, October). Cobalt 2050: Unlocking potential for a net-zero future (Bloomberg NEF report). Retrieved from https://www.cobaltinstitute.org/wp-content/uploads/2024/11/Cobalt-2050_Unlocking-potential-for-a-net-zero-future.pdf

European Commission. (2024, July 4). Commission imposes provisional countervailing duties on imports of battery electric vehicles from China. European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_24_3803

Gold Fields. (2022, October 12). The South Deep Khanyisa solar plant. https://www.goldfields-southdeep.co.za/resources/the-south-deep-solar-plant

Government of Canada. (2023). Budget 2023: A made-in-Canada plan. Government of Canada. https://www.budget.canada.ca

Government of Canada. (2024, July 2). Canada announces 100% surtax on imports of electric vehicles from China. Government of Canada. https://www.canada.ca/en/department-finance/news/2024/07/canada-announces-100-surtax-on-imports-of-electric-vehicles-from-china.html

Government of Chile, Ministry of Energy. (2017). Energy 2050 policy. Santiago: Government of Chile.

International Council on Clean Transportation. (2023, February 6). Battery electric trucks emit 63% less GHG emissions than diesel. International Council on Clean Transportation. https://theicct.org/battery-electric-trucks-emit-63-less-ghg-emissions-than-diesel/

ICMM. (2023, December 5). Accelerating the Adoption of Zero-Emission Haul Trucks in the Mining and Metals Industry. https://www.icmm.com/insights-icsv-initiative

ICMM. (2022, November 14). Collaboration for Innovation: Accelerating the Implementation of Zero Emission Vehicles for the Mining and Metals Industry. https://www.icmm.com/en-gb/comment/2022/accelerating-implementation-of-zero-emission-vehicles

ICMM. (2024, December). Diesel Particulate Matter (DPM) Good Practice Guide. https://www.icmm.com/en-gb/guidance/health-safety/2024/DPM-good-practice-guide

ICMM. (2026, March 10). Global Mining & Metals Greenhouse Gas (GHG) Emissions Dataset. https://www.icmm.com/global-mining-metals-ghg-emissions-dataset

ICMM. (2025, February 15). Mining with principles at Anglo American's Los Bronces copper mine. https://www.icmm.com/en-gb/case-studies/2021/environmental-stewardship/los-bronces

ICMM. (2025, February 15). Mining with principles at Gold Fields' Granny Smith mine. https://www.icmm.com/en-gb/case-studies/2021/environmental-stewardship/granny-smith

ICMM. (2025, October 7). Reflections from Sweden: Collaboration to advance cleaner, safer mining. https://www.icmm.com/en-gb/comment/2025/reflections-from-sweden

ICMM. (2024, August 5). The art of the possible: How collaboration is driving the transformation of large haul truck fleets. https://www.icmm.com/en-gb/comment/2024/art-of-the-possible

International Energy Agency. (2026, January 14). Chile 2050 Energy Transition Roadmap. https://www.iea.org/reports/chile-2050-energy-transition-roadmap

International Energy Agency. (2025, April 10). Energy and AI. https://www.iea.org/reports/energy-and-ai/energy-demand-from-ai

International Energy Agency. (2021). The role of critical minerals in clean energy transitions. International Energy Agency. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

International Energy Agency. (2025). Global critical minerals outlook 2025. Paris: IEA. Retrieved from https://www.iea.org/reports/global-critical-minerals-outlook-2025/overview-of-outlook-for-key-minerals

International Energy Agency (2025, September 12). Global Hydrogen Review 2025. https://www.iea.org/reports/global-hydrogen-review-2025

International Finance Corporation. (2023). Net zero roadmap for copper and nickel mining. International Finance Corporation, World Bank Group. https://www.ifc.org/en/publications/net-zero-roadmap-for-copper-and-nickel-mining

International Mining. (2020, November 24). More OEMs join the ICMM's Innovation for Cleaner and Safer Vehicles initiative. https://im-mining.com/2020/11/24/more-oems-join-the-icmms-innovation-for-cleaner-safer-vehicles-initiative/

International Renewable Energy Agency. (2024, September). Renewable power generation costs in 2023 (Executive summary). IRENA. https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023

McKinsey & Company. (2020, January). Climate risk and decarbonisation: What every mining CEO needs to know. McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/climate-risk-and-decarbonisation-what-every-mining-ceo-needs-to-know

McKinsey & Company. (2023, April 24). Electrifying mines could double their electricity demand. https://www.mckinsey.com/industries/metals-and-mining/our-insights/electrifying-mines-could-double-their-electricity-demand

Mining Magazine. (2023). The Electric Mine. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://new.abb.com/docs/librariesprovider17/process-automation/the-electric-mine-report.pdf

National Renewable Energy Laboratory. (2022). Integrating clean energy into mining operations (U.S. Department of Energy, Technical Report No. 82537). https://www.nrel.gov

Office of the United States Trade Representative. (2024, May 14). ICYMI: U.S. Trade Representative Katherine Tai Delivers Remarks on Her Actions to Increase China Tariffs. https://ustr.gov/about-us/policy-offices/press-office/press-releases/2024/may/icymi-us-trade-representative-katherine-tai-delivers-remarks-her-actions-increase-china-tariffs

Republic of South Africa, National Treasury. (2019). Carbon Tax Act No. 15 of 2019. Pretoria: Government of South Africa.

Reuters Events (2025). Energy Investors Capitalize on Soaring Power Demand. https://1.reutersevents.com/lp=39434

Rocky Mountain Institute (2019). Pulling the Weight of Heavy Truck Decarbonization. https://rmi.org/insight/pulling-the-weight-of-heavy-truck-decarbonization/

United Nations. (2020). Statement by H.E. Xi Jinping at the General Debate of the 75th Session of the United Nations General Assembly. United Nations.

U.S. Department of Energy, Alternative Fuels Data Centre. (2024). Biodiesel benefits and considerations. U.S. Department of Energy. https://afdc.energy.gov/fuels/biodiesel_benefits.html

Vale. (2024, April 15). Vale reaches 100% renewable energy consumption target in Brazil two years ahead of schedule [Press release]. Vale. https://saladeimprensa.vale.com/w/vale-reaches-100-renewable-energy-consumption-target-in-brazil-two-years-ahead-of-schedule

World Energy Council. (2025, February). World Energy Trilemma-Peru. https://www.worldenergy.org/assets/downloads/NON-MC_World_Energy_Trilemma_PERU_Profile_Template.pdf

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