Future Mining Scenarios

Intraw International Raw Materials Observatory

SAFE

The Ambassador Alfred Hoffman, Jr. Center for Critical Minerals Strategy

A forward-looking exploration of the mining industry's future, set against the backdrop of the year 2050

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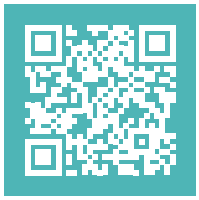


Content

Preface

A stark reality confronts the global economy: the accelerating shift towards advanced manufacturing, digitalisation, and clean energy technologies is driving an unprecedented demand for raw materials and metals. This shift toward a minerals-intensive future, coupled with technological breakthroughs and social transformations, collides with cascading global challenges, making tomorrow's landscape increasingly difficult to forecast, let alone predict. The adoption and deployment of advanced technologies follows a non-linear path, shaped by broader economic conditions, political and regulatory forces, and societal dynamics. Organisations and governments, striving to prepare for what lies ahead, must navigate this complexity with limited resources while traditional power structures evolve, and new global influences emerge. Western economies, in particular, face mounting pressure to diversify and secure critical mineral supply chains — a challenge exacerbated by the mining industry's long lead times and numerous uncertainties surrounding market conditions, operating environments and societal conditions. This kaleidoscope of change requires a nuanced understanding of potential futures.

This factbook presents a forward-looking exploration of the mining industry's future to the year 2050. Our approach combines rigorous analysis with innovative foresight methodologies. We utilised an explorative scenario technique akin to a Delphi process, drawing upon insights from a broad spectrum of experts who contributed their understanding of the forces shaping the mining industry. Their diverse backgrounds enabled us to examine the complex interplay of geopolitical contexts, societal dynamics, technological advances, and environmental challenges, particularly in the realm of extreme climatic events and artificial intelligence (AI) applications.

The analysis yielded nine distinct scenarios, from which we have distilled the four most representative and instructive. These scenarios integrate externalities spanning political, economic, societal, technological, environmental, and legal spheres. They acknowledge the increasingly visible effects of climate change, demographic pressures, health crises and growing economic inequality. While these pressures, combined with rising misinformation and declining institutional trust, create new stress points, we also recognise the potential solutions offered by AI, scientific innovation, and the reimagining of traditional international cooperation frameworks.

We understand that tomorrow's reality is unlikely to align perfectly with any single one of these four scenarios. Instead, the future will likely emerge as a complex weave, incorporating elements from each pathway we describe. These scenarios serve as strategic lenses through which policy-makers and industry leaders can view potential futures and prepare for the ways in which interconnected trends will reshape economies, societal structures, and raw materials supply-webs. They also illuminate the critical inflection points and choices that can steer the world towards one future over the other.

Our ultimate aim is to inspire mining and raw materials organisations to evolve beyond traditional operating models and provide them with tools to navigate future challenges with confidence and purpose.

Key take-aways for policy-makers and industry leaders

The importance of understanding potential mining futures for policy-making

Globally, the mining sector is foundational to a sustained economic development, providing the essential raw materials that form the building blocks for a range of transformative industries such as robotics, digital infrastructure, AI, and clean energy. For resource-rich countries, it also serves as a crucial driver of economic development. However, the industry is grappling with unprecedented challenges, including intensifying geopolitical tensions, opaque and manipulated markets, mounting environmental concerns, and increasingly complex social license to operate issues.

These scenario analyses serve as a strategic tool rather than a predictive exercise. Their primary purpose is to stretch thinking and enable future-proofed strategies in two critical ways:

- Supporting policy-makers in designing resilient policies that can withstand various potential futures,
- Illustrating how policy decisions today can influence which scenario materialises, recognising that the future remains malleable and will likely combine elements from several scenarios.

The analyses emphasise that geopolitics and policy choices, both domestic and international, will fundamentally shape the future trajectory of raw materials supply. The actions of policy-makers, companies, investors, and communities will collectively determine which elements of these scenarios become reality.

The scenarios and their implications

The analysis presents four distinct scenarios for the future of raw materials supply:

The Advancement Wave

A technology boom drives substantial productivity gains and societal benefits in well-capitalised countries, transforming transportation, energy systems, and manufacturing whilst boosting climate resilience. Trade blocs work to restrict technology diffusion to rivals to maintain their competitive edge, while uneven access to technology and capital within blocs exacerbates inequality between developed and developing nations.

Divided Dominions

Fragmented trade blocs distort minerals and metals markets, imperil economic development and weaken both extraction and recycling industries. Limited international cooperation hampers innovation and sustainable development, while diverging standards create inefficiencies.

Downward Spiral

Resource nationalism breeds global and domestic instability, leading to economic volatility and environmental degradation. International cooperation collapses as countries pursue self-sufficiency, resulting in inefficient duplication of efforts and increased conflicts.

The Great Transition

A global catastrophe serves as a catalyst for unprecedented international cooperation, leading to a transformed society focused on sustainability and shared prosperity. This scenario features strong multilateral coordination, harmonised standards, and accelerated technological innovation serving collective interests.

Strategic imperatives and path forward

The concentration of critical mineral supply chains in a single country creates legitimate national and economic security concerns about supply disruptions and geopolitical risks. Since the recent pandemic exposed supply chain vulnerabilities, countries started responding with varying approaches.

The United States deployed a range of policy tools — from Defence Production Act authorisations to funding programmes under the Bipartisan Infrastructure Law and Inflation Reduction Act — aimed at incentivising domestic capacity building and promoting supply from more secure sources. Financing tools through the Export-Import Bank and Development Finance Corporation were directed towards overseas critical minerals projects that strengthen supply chain security and create commercial opportunities for U.S. industry, while closer collaboration with allies focused on developing strategies to collectively address anti-competitive behaviour in global markets. Finally, the United States have been more proactive in using trade tools to protect their domestic industries.

In contrast, the European Union takes a multi-pronged approach through its Critical Raw Materials Act, building on three pillars:

- The first pillar strengthens domestic capabilities by targeting 10% extraction, 40% processing, and 15% recycling of annual EU consumption by 2030. It accelerates strategic project permitting while advancing research and innovation.
- The second pillar creates partnerships with aligned resource-rich nations through joint ventures, technology transfer, EU development funding, and dedicated cooperation platforms.
- The third pillar enhances supply security via EU-wide risk monitoring, strategic stockpiling, joint procurement, supply chain certification, and trade defence mechanisms. This integrated approach aims to secure 25% of EU critical materials needs through reliable partnerships by 2030.

Both approaches emphasize domestic capacity, international partnerships, and market protection, though the EU framework provides more specific targets and structured mechanisms.

Global developments — including US and EU policies to date — suggest a movement towards the Divided Dominions and Advancement Wave scenarios. While concerning signs of trade tensions and bloc formation emerge, examples of successful international cooperation persist. The status quo in 2024 shows a worrying tilt towards fragmentation, with policies not yet optimised for sustainable, responsible mining to support global development. Yet our trajectory towards 2050 remains far from certain — all futures, including Downward Spiral and Great Transition, remain possible. Recent EU and US elections are poised to reshape the political landscape, potentially bringing substantial shifts in policies impacting the mining sector. Similar political transitions worldwide could further reshape how nations approach domestic critical minerals development and international cooperation. Understanding what drives different outcomes is therefore crucial.

Five factors emerge as fundamental differentiators between the four scenarios for the mining sector's future: First is the extent of technological innovation adoption across the mining value chain. Breakthrough technologies, including spill-over advances from other industries, can transform mining operations by improving productivity, reducing operational costs, enhancing supply chain transparency, minimising environmental impact, and helping address persistent workforce challenges through automation and digital solutions. Second is improving societal acceptance of mining operations through meaningful community engagement, equitable benefit sharing, and demonstrated environmental stewardship. Third is the establishment of stable, predictable policy frameworks that provide the certainty needed for long-term investment and strategic planning. Fourth is managing demand volatility through mechanisms such as long-term contracts, public procurement policies, and market-making instruments that provide greater certainty for investors, producers and consumers alike. Fifth is the degree of international cooperation versus zero-sum competition. While some policy-makers may lean towards protectionist strategies and domestic-first policies, the most successful paths forward strengthen national capabilities while also maintaining some level of international cooperation.

To move towards the more positive outcome, policy-makers must take several decisive actions:

1. **Maintaining strong public support for mining and materials processing R&D through grants, loans, and research hubs remains crucial.** This support should prioritise innovation and commercialisation of technologies that reduce costs, improve efficiency, and mitigate environmental impacts while fostering cross-sectoral collaboration. The success of initiatives such as the US-EU-allied collaboration on technology development, including partnerships with Japan and South Korea, demonstrates the potential of international cooperation.
2. **Improve societal acceptance of mining through two complementary approaches.** Building on recent efforts under the CRMA and the 2023 debt ceiling bill in the United States, the permitting process needs reforms focused on clarity of rules, objectivity of decision-making, and efficiency of execution — improvements that can not only streamline permitting but also help build trust in the process itself. Second, governments must clearly define relevant stakeholders and establish frameworks for meaningful engagement in the permitting process to ensure that affected communities see visible benefits from resource development.
3. **Create mechanisms to minimise cyclicity and de-risk investments in critical minerals projects.** This requires both, supporting the deployment of mineral-intensive energy technologies and digital infrastructure, while simultaneously creating policy incentives for downstream manufacturers to diversify supply sources. For critical raw material producers, market certainty can be strengthened through mechanisms such as offtake agreements, long-term contracts, and metal-backed exchange-traded funds. Complementing these efforts, public procurement policies can shape demand patterns while promoting recycling and circular economy initiatives that create additional stability in materials markets.
4. **Enhance multilateral cooperation.** Existing fora offer valuable platforms for technological and socio-economic progress. The G7 can develop sustainable standards and enhance industry transparency, while the Mineral Security Partnership and various bilateral and multilateral working groups can support high-standard mining projects that diversify global supply chains. These efforts require strengthened dialogue between public and private sectors, pooled funding mechanisms, and state guarantees to de-risk strategic projects. Bilateral and multilateral trade agreements can further facilitate the flow of responsibly produced minerals and metals.
5. **Move beyond short-term electoral cycles to focus on long-term strategic planning.** Success requires sustained political commitment and policy stability across electoral cycles, along with getting the balance right - between domestic security and international cooperation, between environmental protection and economic development, between local impacts and global benefits - to avoid the pitfalls of the «Downward Spiral» and «Divided Dominions» scenarios, while capturing the opportunities presented by technological advancement and international collaboration.

Methodology

This publication provides a forecast for the future of the mining industry in 2050. The experts that developed these future scenarios followed a structured approach, employing the scenario technique. This method provides insights into an unpredictable future based on well-elaborated factors and dynamics that shape our world. The scenario technique combines knowledge from sectoral experts with sophisticated strategic foresight methods leveraging economic, political, technological, environmental and social trends and responses.

The approach underlying the scenarios presented in this booklet comprises 5 major steps (Fig. 1). It begins with the identification and clustering of relevant influence factors, followed by a cross-impact analysis. The process culminates in the development of narratives that are based on projections of the identified influence factors.

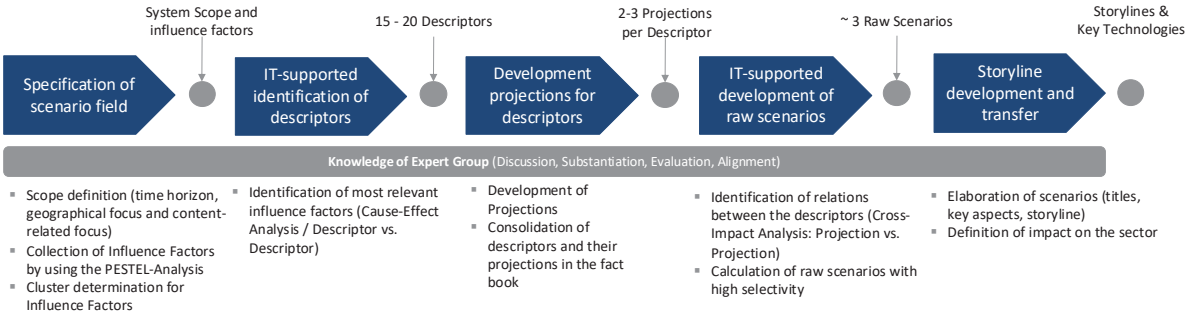


Figure 1: Scenario procedure flowchart.

The joint team from the United States and Europe combined their expertise using the PESTEL framework to comprehensively analyse the future environment of the mining sector. During two workshops held online and physically in April 2023 in Brussels, they identified 20 main factors driving the mining industry in 2050. The system grid presented below (Fig. 2) summarises these main factors, with their relevance to future scenarios, decreasing from the top right to the bottom left of the illustration.

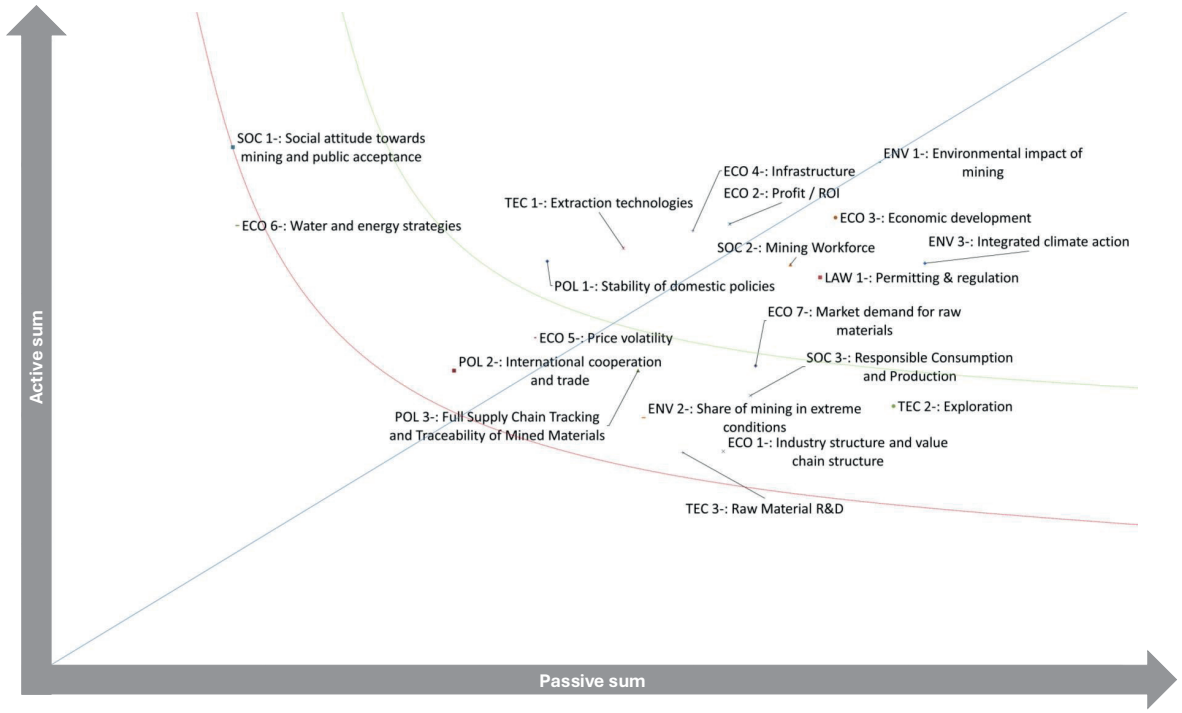


Figure 2: Relevance of main factors for the future scenarios (system grid).

Following this step, robust projections for these influence factors were iteratively developed, consolidated in a fact book and matched through a cross-impact analysis. The analysis included comparison of all projections in pairs to address the viability of their co-existence in the future. For each influence factor, experts developed between two and four meaningful projections, describing the elaboration of the different influence factors in 2050. A software-based matching of the different projections using the Cross-Impact Balances method (CIB) and the ScenarioWizard Tool of the CIB-Lab (University of Stuttgart) ultimately yielded nine scenarios. Subsequently experts clustered these nine scenarios into four raw scenario clusters (Fig. 3).

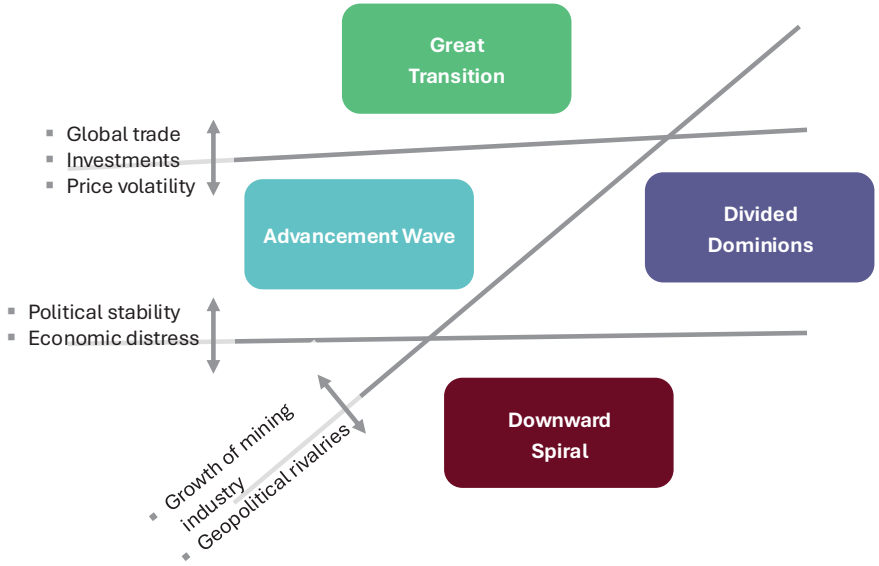


Figure 3: Final four raw scenario clusters developed.

By early 2024, each scenario cluster evolved into a fact-based elaborated narrative. The core team of experts from the United States and Europe developed these narratives iteratively through a series of workshops. Each storyline follows the same systematic structure. Starting with an explanation of the global political climate aligned with the future economic situation, the societal and environmental situation in 2050 is outlined. For each of the four narratives, the future in the mining value chain and the technological progress of the mining industry are projected based on these overarching developments. Winners, losers and main protagonists provide insight into the balance of power between stakeholders in the raw materials sector, including governments at all levels, industrial sectors, civil society, and global organizations. Finally, potential disruptions that might impact the determined transition are identified.

The world of raw materials in 2050

Divided Dominions

Self-contained blocs imperil economic growth and development

Amidst escalating geopolitical rivalries, the emergence of self-contained trade blocs with conflicting worldviews post-2030 results in substantial market distortion, imperilling research, innovation, and the energy transition, yielding only modest, long-term economic growth and fostering social unrest in developed and developing countries.

Key aspects

Persistent grievances over influence, power, and wealth distribution drove deglobalization leading to the establishment of self-contained trade blocs built on distinct approaches to global issues and economic and social governance with virtually no cross-bloc investment, trade or technological cooperation. This new system is predominantly shaped by dominant major powers and their interests, aimed at bolstering the competitiveness of critical industries such as AI, space, defence, communications, electronics, and health. Other nations face mounting pressure to align exclusively with on bloc. Recognized that domestic raw materials endowments could not sustain downstream manufacturing needs, major countries worked with other like-minded countries for raw material access for domestic industries. In response, excluded nations formed alliances and obstructed the export of critical raw materials to "elite blocs." Regional conflicts and proxy wars became commonplace, fuelled by historical animosities. Fragile peace is consistently under threat of conflicts where alliances are not sacred, and opportunism and "realpolitik" prevail.

The geopolitical schisms volatilized critical raw materials markets, undermining long-term development. While there were opportunities for limited technological improvements and efficiency gains, a weakened extraction and recycling industry failed to realize robust investments and growth, leading to economy-wide impacts of an inefficient raw materials supply chain.

International Cooperation and Domestic Policies

- Trade blocs are based on factors such as former military alliances, ideological alignment, and language. Fierce competition among blocs has fragmented markets with limited trade between blocs.
- The fragmentation severely hampers global cooperation across issues of sustainable development, climate action, humanitarian aid, migration, public health, and poverty reduction. The United Nations (UN) and other bodies struggle to broker even modest accords among distrustful blocs. Official development assistance is often tied coercively to the strategic interests of patron states. Dissent within blocs is met with threats of expulsion or isolation.
- Supply chains are vulnerable to disruptions as the small number of suppliers and potential buyers operating within each trade bloc is a limited buffer against demand and supply shocks.
- Developing nation bloc members with unique resources leverage their position to play bloc leaders off each other, switching bloc alignments when advantageous.

Economic Situation

- The fragmentation has ruptured integrated supply chains and demand dynamics across sectors, resulting in severe commodity price volatilities, market uncertainties, and speculation-fuelled hoarding within blocs. Stranded assets and redundant capacities cause misallocation across infrastructure.
- Growth prospects drastically diverged between blocs as zero-sum mentalities supersede cooperative advancement. Despite rising green technology demand, scaling constraints persist from chronic underinvestment, skills gaps, and bottlenecked logistics.
- Uneven, intra-bloc development has deepened societal rifts whenever governance was captured by entrenched blocs favouring militarisation and industrial subsidies to select interest groups, while other socio-economic issues are sidelined.
- Capital is captive within blocs, and with low economic growth, capital returns are low thus limiting reinvestment opportunities.

Society and Environmental Aspects

- The cascade of economic and political disruptions drives waves of mass migration, civil unrest, and ideological extremism, overwhelming fragile governments. Hollowed-out public sectors are unable to deliver essential services leading to expansion of shadow networks and militant factions.
- Severely weakened international organizations are unable to provide any real influence on addressing of global concerns, such as climate change impacts.
- Excluded communities face soaring inequality and climate vulnerability with minimal state or international support. Perpetual uncertainty and precarity fuel sectarian tensions and regression of social progress.
- Geopolitical instability has derailed climate commitments, with bloc leaders deprioritizing threats that required cooperative action. Environmental oversight capacity has declined amidst deregulation drives to spur industrial self-sufficiency. With the demand for critical raw materials rising, irresponsible extraction practices expand, especially where civic activism is suppressed.
- Volatile commodity prices strain responsible miners trying to balance profitability with duty of care.
- Some progressive national governments and regions are trying to lead by example but face difficulties mobilising partners across business, civil society, and science to support systemic change.

The Mining Value Chain and Mining Technologies

- The accelerating mines-to-market rivalries prompt major powers to invoke defence priorities across minerals supply chains thus redirecting outputs towards domestic manufacturers. Smaller bloc players face squeezed access, forcing higher cost substitutions. Upstream specialisation has increased within blocs but stifled overall optimisation.
- Heavy state interference skews commercial drivers. Investment flowed into large-scale projects, but lagging state-owned conglomerates in developing countries focus on import replacement rather than innovation to bring step-change solutions.
- Responsible mining struggles as price volatility and policy unpredictability hamper compliance budgets.
- Diverging standards across competing blocs create interoperability challenges, slowing the diffusion of breakthrough innovations like automation and AI analytics. First-mover blocs restrict sensitive technology transfers and poached talent.
- While recycling and substitution progress continue, increasing opportunity costs from severed R&D linkages delay technology diffusion.
- Small enclaves within major blocs discreetly collaborate across borders, laying the groundwork to propel circular value chains.

International Cooperation and Domestic Policies

International Cooperation and Trade

Rising nationalist sentiment and major power rivalries have driven dominant countries to abandon cooperative global systems and construct restrictive trading blocs centred on boosting domestic industries. These major bloc powers utilise protectionist tools like discriminatory standards, punitive tariffs and bans on certain imports/exports to severely limit trade and collaboration between rival blocs.

Smaller mineral-producing nations are coerced through diplomatic and economic pressure to participating in one of the rival trading blocs. Their allegiances frequently shift based on who provides better patronage rather than shared values and mutual interests. The fracturing of integrated global supply chains into isolated trifurcated networks enable internal bloc flow of goods and capital at the expense of overall market stability, efficiency, and innovation potential.

Stability of Domestic Policies

The dominant bloc powers maintain stable priorities to bolster their global position. Cooperation on transnational issues like climate change, pandemics, and inequality are severely hampered by zero-sum mentalities and a narrow focus on mitigating impacts on the bloc. While regime changes occur, successor governments adopt status quo policies due to pressures from entrenched militaristic and corporatist factions who benefit most from the status quo of continued geopolitical tensions.

Reform attempts are thwarted as political leaders use nationalism and external threats to channel public frustration away from underlying domestic governance failures. Civic dissent and demands for accountability face crackdowns justified as pre-empting foreign subversion. The divide is a self-fulfilling cycle bereft of collective leadership on shared planetary challenges.

Major powers have sacrificed global cooperation and ethics at the altar of parochial interests tied to dominating rivals — forcing smaller nations into arrangements that erode universal progress. Reversing this fragmentation requires inclusive civic movements centred on pluralism, transparency, and prosperity.

Economic Situation

Infrastructure

The fragmentation into trade bloc markets has increased risks and uncertainty through reduced diversity of capital, reducing return on investments in mining projects and associated infrastructure. Many miners postpone upgrades and maintenance which is leading to accelerated deterioration of roads, bridges, rail lines, etc., which are all vital for operations. Over time, subpar infrastructure networks are imposing hard limits on reliable mineral extraction and export volumes globally. Logistical bottlenecks and supply chain inefficiencies are commonplace with most mining companies struggling to navigate regional transport links.

Price Volatility

Frequent commodity boom and bust cycles within trade blocs make mining projects increasingly risky as price forecasting models are challenging and capital markets less diverse. The concentrated markets mean that a few key players can create exaggerated ripple effects. While some miners sporadically benefit from cycles, the volatility generally hampers rational expansion plans thus slowing productivity growth. Buyers also swing between delaying purchases or hoarding based on extreme price swings.

Commodities largely sourced from lesser-developed nations are particularly positioned to influence pricing within a given bloc. By leveraging their unique role in supporting economic activities, they shift allegiance to blocs with the best offer, creating additional pricing volatility within a bloc but not necessarily globally.

Economic Development

The loss of positive external impacts from mining growth and global integration inhibits broader economic development. Global GDP continues to limp around 2-3% annually, mainly driven by trade within individual blocs rather than globally. Furthermore, the inclination towards economic nationalism and growing distrust, even within trading partnerships, hampers cross-border investments crucial for balancing the impacts of dwindling private sector infrastructure financing. Supply disruptions and declining productivity instigate prolonged economic stagnation, posing particularly severe challenges for developing countries.

Responsible Consumption and Production

High market volatility and geopolitical rifts foster tendencies towards short-term commercial interests over responsible production despite initial drivers to bolster supply chain nationalisation and sustainability-advancing industries domestically. With demand still rising for critical raw materials, most miners satisfy minimal standards rather than proactively promoting the adoption of best practices for sustainable mining and processing. Lagging adoption is most severe where public/democratic oversight is suppressed and an authoritarian government exists. Nevertheless, progressive governments and civic movements focus on transparency, equity, and ethics spearheading innovation partnerships between like-minded states and responsible businesses.

Environmental Impact of Mining

Environmental impact trajectories diverge between developed and developing country miners - the former progressively adopting emission controls, water preservation etc., due to market pressures and rising public climate concerns; the latter still struggling from financial constraints and governance gaps preventing uptake of expensive sustainability upgrades - except responsible global (or bloc-wide) miners that uniformly adopted best practices irrespective of operating geography. However, the overall net impact increases irresponsible extraction given demand increases, downstream pressure to reduce input costs, and weak enforcement capacities from disjointed global agreements and prioritization on bloc growth.

Social Attitude towards Mining, Public Acceptance

Initial acceptance of mining's importance for self-sufficiency has given way to growing public scepticism and pockets of resistance, fuelled by lagging transparency, captured local benefits, and recurring environmental incidents that strain community trust. Repeated ownership changes, uneven local hiring and weak environmental rehabilitation commitments also erode public trust. Risks of social unrest are high, particularly where income inequality, vulnerability gaps, and civic voice deficits grow with economic instability and authoritarian policies that mute equitable advancement.

Mining Workforce

Self-contained trade blocs severely impact labour flow, which is driving acute shortages, especially in productivity-increasing skilled roles like processing, equipment maintenance, analytics, etc. Attempts to compensate through automation negatively impacts community support due to a reduction in visible hiring. Attracting talent necessitates drastic measures like exempting miners from military conscription alongside rising wages thus straining small operators. Targeted reskilling programs were curtailed and impeded by insularity priorities. Skills shortages remain a bottleneck driven by a lack of cooperation to align training, labour mobility, and incentives to meet demand.

Integrated Climate Action

High market uncertainty discourages most miners from significantly investing to meet the Paris Agreement's climate ambitions. Momentum loss was partially substituted where national governments instituted rigorous emissions caps, set bold demand signals, and enabled risk-sharing schemes that guaranteed adequate returns. But discordance across fragmented policy spaces neutralised the impact of such pockets of progress. Without cooperative incentives and commercial drivers aligned with climate policy signals, most companies hesitate on actions beyond operational efficiency or adjusting to local regulations.

The Mining Value Chain and Mining Technologies

Market Demand for Raw Materials

Under worsening recessions and continued market uncertainty, critical raw materials demand languishes. Prices plunge forcing affected miners to scale back high-cost operations and slash expenditures on exploration, new projects, and expansions, and only retain the lowest-cost mines. A prolonged downturn bankrupted miners lacking financial depth, further concentrating supply. Without cooperation to align demand signals and smooth the technology adoption curve for mineral-intensive applications, these conditions are entrenched amidst weak investment.

Industry Structure and Value Chain Structure

The pursuit of efficiencies drives outsourcing of non-core mining competencies to contractors and Original Equipment Manufacturers. Undercapitalized miners trade equity to secure offtake agreements and risk-sharing with major manufacturers across sectors like defence, automotive and electronics – generating stable demand amidst volatile markets. Reliance on downstream players has increased despite earlier ambitions of achieving self-sufficiency across all raw material supply chain stages. Collaborative specialisation helps adequately capitalised miners enhance productivity.

Raw Material R&D

High mineral price volatility drives investment in R&D for recycling and substitution to bypass exaggerated trade bloc supply-demand imbalances and lower primary production dependence. However, progress remains confined to developed country blocs with financing capacities, stable policy incentives for commercialisation, and sustainability-conscious consumer demand. Computing, automation, and material breakthroughs are dramatically improving the viability of urban mining, battery chemical reclamation, etc., but diffusion barriers limited global gains.

Extraction Technologies

The adoption of automation, data analytics and interconnected industrial hardware across mining operations have boosted productivity, real-time supply-demand modulation, and predictive maintenance to insulate against external volatility. Critical advances include autonomous haul vehicles, AI for exploration and mining operations and drone surveying, enabling continuous operation. However, even with lower employment intensities, the technologies alone haven't resolved acute labour and skills shortages, and miners have increased recruiting budgets to lure digitally adept talent away from other sectors.

Winners

Industry

- Low-cost mineral producers are more resilient to market fluctuations. These producers have deposits that are cheaper to exploit and/or can reduce production costs through technology R&D and increased efficiency.
- Mineral producers that enjoy a competitive advantage solely based on their geographical location.
- State-owned miners, aligned with governing regimes for patronage and growth.
- Tech companies.
- Highly skilled workers specialized in emerging technologies.
- Speculators, profiting from high commodity price volatility.

Regions, Organizations, and others

- Dominant bloc powers able to push partisan interests using economic and military power.
- Most developed economies.
- A small proportion of developing countries with rich resources and near-shoring opportunities to support their bloc's lead powers.
- Countries with good geological endowments and existing infrastructure.

Loosers

Industry

- High-cost producers in blocs with an oversupply of minerals.
- Small miners in developing countries that lack resources to adopt best practices.
- Mining innovators struggling from dampened investment and unstable policies.
- Mining companies lacking advanced capabilities.
- OEMs and consumers in trade blocs facing supply shortages.

Regions, Organizations, and others

- Future generations.
- A large proportion of developing countries.
- Multilateral institutions, unable to broker. meaningful accords across hostile blocs/Global institutions like UN, G20, WTO, ICC.
- Citizens in totalitarian regimes face repression and stifled dissent and liberties.
- Global tourism.

Protagonists

- Major power blocs' leaders aggressively pushing partisan agendas.
- State-backed miners, aligned with governing regimes for patronage.
- Developing nations with unique resources of global demand.
- Speculators and middlemen exploiting volatility for profits.
- Multilateralists aiming to heal rifts by aligning incentives.
- Activist citizens pressuring blocs on sustainability and rights failures.
- Academics/developers of breakthrough technologies.
- Intra-bloc financial institutions (banks from developed countries within specific bloc).

Disruptions

Geopolitical:

- Progressive political leadership capable of messaging shared interests over wedge issues.
- Violent conflicts spurring on peace movements.
- Growing resource nationalism (even a trade bloc can be seen as too much trade).

Economic:

- Discoveries enabling abundant, low-cost clean energy could remove scarcity-driven resource conflicts.
- Younger generations prizing sustainability and cooperation, could drive policy shifts when in power.

Social:

- Public health emergencies creating openings for scientific collaboration across borders.

Environmental:

- Catastrophic extreme weather events could force cooperation to build climate resilience amidst common threats.

Advancement Wave

A technology boom drives progress but widens inequality

The world is divided in trade blocs, and while most developed nations reaped substantial economic growth and modernisation from the massive global push to rapidly transition energy systems during the 2030s, less-developed countries either found a track of low investment capital and technical capabilities and struggled to accelerate their development or a track of maximizing the impact of resource development into critical raw materials that were then used as leverage within and between trade blocs, creating a shadow pole of power.

Key aspects

The massive global push to rapidly transition energy systems that started in the late 2020s and continued in the following decades sparked an intense technology race reminiscent of the 1960's space race and 1990's dotcom booms. As leading economies poured funding into green innovation, breakthroughs in areas like batteries, AI, robotics, quantum computing, and fusion energy catalysed exceptional advancements. Dubbed the "Advancement Wave", this technology boom has delivered enormous productivity gains and societal benefits to well-capitalized countries transforming transportation, energy production and distribution, manufacturing, and resilience against climate change impacts. However, intellectual property concerns and ineffective tools for technology transfer limit the impacts of these advancements in the developing world, which has exacerbated global inequality and impeded universal social advancement.

Regional trade blocs, anchored by major global players, seek to limit technology diffusion to geopolitical rivals. Knowledge hoarding and technological nationalism are strategic barriers separated along ideological lines. Some investment and technology transfers occur to lesser-developed players inside the trade blocs when it is advantageous to the major players.

These lesser-developed players, especially those with key mineral resources, leverage those resources in their relationship to their patron trade bloc. Periodically, some developing nations switch bloc loyalties while others engage with multiple blocs to reap fresh investment and political clout.

Global cooperation diminished as advanced economies turned their focus inward creating growing divergence that accentuated international inequalities and strained collaborative efforts on a global scale, particularly between blocs. Despite notable progress in mitigating CO_2 emissions and the positive impacts of emerging technologies, the uneven diffusion of these advancements has deepened divides. Poorer countries face climate vulnerability and social unrest, resulting in continuous population outflow towards advanced countries and blocs thus further impeding their economic development.

International Cooperation and Domestic Policies

- Innovation within trade blocs catalyses greater integration of supply chains and collaboration between allied nations with shared priorities.
- Massive investments in domestic education, research, and localisation initiatives seek to consolidate strategic advantages.
- International forums have evolved into formations of ideological camps focused on advancing their societal/political visions rather than global-benefiting consensus. This fracturing occasionally fuels localised armed conflicts, especially in the blocs-borders regions.
- Treaties emphasize intellectual property protections, standards promotion, and joint climate resilience projects among bloc members.
- Countries outside of the bloc cores struggle by all socio-economic metrics and some have become client states of specific blocs with little autonomy or measured benefit.

Economic Situation

- Soaring consumer demand for green products, smart homes, and climate resilience services fuel intense growth in industries advancing sustainability technologies.
- Government stimuli and unprecedented private investment capital propel markets as blocs economically compete. Startups proliferate while pioneering sectors experienced labour shortages even with pan-bloc recruitment.
- Speculative investing continues into new tech firms and crypto assets tied to the Advancement Wave, resulting in bubbles. Volatile markets and cycles of exuberance among retail investors became a fixture during and after the 2030s, acting as a drag on investments in traditional industries.
- Limits on technology transfer, coupled with rapid capital shifts towards green energy, has made many developing nations suffer increased energy poverty for the lack of available infrastructure development.

Society and Environmental Aspects

- Intra-bloc focus on innovation spurs optimism on tackling pressing issues like curbing CO_2 emissions and responding to climate disasters.
- Public-private partnerships around space colonisation and climate restoration moonshot projects captured imaginations as competition between blocs increases even with general shared goals.
- World leaders recognize common inter-bloc issues and embrace technology to resolve climate resilience challenges at the 2030 Sustainable Development Goals review.
- By 2040, social standards rose across all industries. Clean electrification, agricultural efficiency gains, and disaster-resilience systems brought stability for some regions.
- Limited access to novel technologies and emerging solutions exacerbate inequality between developed and developing nations.
- Researchers identified irreversible climate thresholds, tempering hopes for a full recovery of climate.

The Mining Value Chain and Mining Technologies

- Spillover technologies, like robotics and battery advances, transform mining business and practice despite persistent skills gaps.
- Electrified equipment and continuous remote operation improve productivity and safety.
- Advances in spatial data analytics accelerate identification of new deposits.
- Modular pilot plants demonstrate the feasibility of compact material processing units.
- Investors eagerly fund startups using space-derived and AI techniques for exploration, advancing deep-sea and ultra-depth mining and developing nanoscale technologies for processing and recycling operations.
- University partnerships with miners upgrade regional workforces. But demand still strains capacity, with mines struggling to keep pace with material needs for transport decarbonisation and domestic/regional climate adaptation megaprojects.
- Knowledge drain from poorer countries continues to aggravate the knowledge divide between developed and developing countries.
- Recycling is deeply integrated into the mining industry, with companies investing heavily in infrastructure and technology to capture, process, and reintegrate secondary materials into production. This reduces the industry's reliance on primary resources and creates new economic opportunities in recycling and waste management as they become raw material companies.
- Efficient resource usage is a cornerstone across the mining value chain, strengthening its ability to respond to market shifts and supply chain disruptions.

International Cooperation and Domestic Policies

International Cooperation and Trade

The era of multilateralism and extensive global exchange gave way to a divided international order. Regional trade blocs, anchored by major global players, follow their own unique values and priorities. Cooperation and trade no longer stem primarily from shared economic interests but are driven by ideological allegiances. Inside these self-contained blocs, innovation is flourishing as they compete in a relentless technology race. Enormous investments in education, research, and internal initiatives have not only solidified their strategic advantages but also fostered bloc-level self-sufficiency by reducing external dependencies. Supply chains weave the economies of bloc members into tightly integrated networks that are occasionally disturbed by individual, opportunistic "side-switchers" and source countries that remain outside of formal trade blocs and thus tend to be less stable economically and politically. The rapid pace of innovation fuels intra-bloc economic integration, enhancing efficiency and resilience. Once hubs for global consensus, international forums are arenas where ideological posturing takes centre stage. Instead of seeking global agreement, these forums have split into ideological camps, each bloc focused on advancing its own societal and political vision. Treaties have shifted their focus from promoting global trade to safeguarding intellectual property, enforcing tech and mining standards specific to each bloc, and supporting joint climate resilience and adaptation among members. Global trade remains at risk, even within blocs, as climate disruptions and periodic proxy conflicts erupt leading to new areas too dangerous to operate or transport through, and ongoing risks of malicious operator attacks on international trade routes continue, with global policing interests now driven by opportunistic powers within each bloc.

Government Regulation and Stability of Domestic Policies

Stable domestic policies and government regulations align with the energy transition and provide raw materials investors unparalleled confidence as they navigated the various stages of project development, from exploration to permitting and construction. Moreover, within trade blocs, minimal country risk premiums result in reduced capital costs for raw materials and infrastructure projects. This cost reduction has improved the return on investment for these projects and made them more appealing to equity investors.

Economic Situation

Economic Development

The fragmentation of the global market, initially perceived as a source of instability, paradoxically ignited economic growth. Countries within trade blocs recognised their mutual interdependence and embarked on collaborative initiatives, fostering a period of sustained expansion and revitalised dynamism not seen since the 1990's dotcom boom. Three key developments and trends propelled this boom:

- Technological breakthroughs in AI, robotics, quantum computing, and energy production.
- Decarbonisation efforts and cost competitive advanced energy technologies in developed countries boosting infrastructure investment.
- Rising wealth in developed regions supporting domestic investment.

However, labour shortages are a challenge, even with recruitment efforts abroad, as pioneering sectors expand rapidly. This has led to some policy conflicts within blocs, but they remain at the diplomatic level. Additionally, risky speculation emerged around new tech firms and assets associated with the Advancement Wave, leading to market bubbles and volatility. This pattern of exuberance among tech investors persisted through and beyond the 2030s. The critical limiter on growth has been the finite capital availability within each trade bloc, but in the long term has supported stronger direct reinvestment in the same economic spaces.

The inequities between developed and developing nations remain, and those countries outside of trade blocs suffer the most for lack of access to technology or capital. Selected developing nations are rapidly developing by being critical suppliers within a bloc and leverage this influence for economic and political gain.

Infrastructure

Extreme climatic events often disrupt raw materials production, processing, and transportation infrastructure, bottlenecking supply chains. For this reason, competitive dynamics in mining has shifted towards near-market projects or to well-connected locales. Nevertheless, discoveries in untapped regions drive substantial government investments in infrastructure including roads, rail, and ports linking raw materials production areas to export hubs. Remote and overseas sources that require marine-based transport are weak links in the mining chain due to their exposure to raids and conflicts because of their unprotected duration in international waters. Additional investments in power production and distribution, water supply, and telecom connectivity to increase climate resilience improve local development and spur broader infrastructure expansion.

Economic Situation

Price Volatility

Soaring consumer demand for sustainable products and climate resilience services, driven by government incentives and private investments, gives pricing power for producers of raw materials used in these technologies. Labour shortages, risky speculation in tech firms and assets, market bubbles, and formal and informal global conflicts introduce short-term price volatility that sporadically affects the raw materials sector. Additionally, disruptions by extreme climatic events, and competition for resources in certain regions, create supply chain bottlenecks, leading to sporadic price spikes for specific raw materials.

Profit

Companies and investors expanding production of critical raw materials now enjoy substantial returns, driven by:

- Growing and sustained demand for raw materials crucial for clean energy technologies.
- Robotic technology adoption, enhancing precision and efficiency in small, high-grade deposit extraction.
- Supportive jurisdictions streamlining permitting and investing in infrastructure.

Society and Environmental Aspects

Social Attitude towards Mining, Public Acceptance

In the early 2030s, optimism pervaded global society fuelled by breakthrough innovations to address urgent challenges like CO_2 emissions and climate impacts. Public-private partnerships centred around ambitious space colonisation and climate restoration initiatives captured the collective imagination. World leaders embraced technology to tackle climate resilience issues during the 2030 Sustainable Development Goals review. By 2040, social standards had improved across various industries. Access to clean, low cost, reliable power, agricultural efficiency gains, and robust disaster-resilience systems have increased stability in many regions. Raw materials production is perceived as a necessity to achieve energy transition objectives and safeguard the strategic autonomy of countries and the stability of blocs. Mining has gained some level of social tolerance and acceptance as a vital industry. Nevertheless, some mining projects compete with local communities for essential resources like water, causing localised public opposition to mining.

Mining Workforce

As the demand for raw materials surged, labour costs within the mining industry soared. The heightened competition for skilled workers among numerous projects has intensified the race for existing talent. Raw materials producers use strategic workforce management practices to optimise production while contending with the limitations of a limited pool of experienced personnel. This has catalysed the adoption of automation and robotics within the raw materials sector as companies seek innovative solutions to augment their labour force and enhance operational efficiency. Despite the diversification of the mining industry and inclusion of local communities in their operational decisions, automatization and robotisation has decreased aggregate employment in the populated mining regions for less-skilled labour, especially in developing countries, which is further exacerbating the difference in living standards within blocs.

Responsible Consumption and Production

The major trading blocs prioritise self-sufficiency and innovation making sustainability practices, such as efficient resource use, waste reduction, and environmentally friendly production, essential for long-term resilience. Responsible consumption and production standards and practices, fostered by industries and public-private partnerships, are common amid technological advances and decarbonisation efforts.

Integrated Climate Action

In the early 2030s, technological innovations enabled the reduction of CO_2 emissions and response to escalating climate impacts. By 2040, regions that embraced clean electrification and robust disaster-resilience systems experienced newfound stability. The raw materials industry, driven by policy incentives to accelerate the energy transition, scaled up the production of essential metals for electric vehicle batteries and renewable energy technologies. A transformative shift occurred in the mining industry, as major miners transitioned from extractors to raw material providers to actively promoting circular economy models by capturing value through the entire cycle. These "material providers" now forge close bonds with the communities surrounding their mines, fostering economic and social inclusion and dedicating revenues to climate resilience projects. This progressive approach supports public acceptance of the sector and accelerates innovations around mining areas, including enhanced CO_2 storage, primary hydrogen production, and alternative process chemistries to mitigate emissions.

Even as these positive changes unfold, a stark divide persists globally. Lacking access to novel technologies and emerging solutions, less developed countries within each trade bloc struggle to keep pace with their more advanced counterparts. Additional-

ly, disquieting research on irreversible climate thresholds casts a shadow of uncertainty over hopes for the future and identifies increased risks for countries without access to the advanced technologies to support climate impact mitigation.

Water and Energy Strategies

Breakthrough technologies like nuclear fusion and water recycling enables unlimited and affordable water and energy resources, driving mining expansion into previously constrained regions and benefiting remote areas globally. The raw materials producers embrace sustainability, on-site renewable power generation, and reducing energy-intensive processes. However, recurrent extreme climatic events strain raw materials production. While stockpiling is effective in curbing the negative effects of disruptions for speciality metals, major commodities such as iron, copper, zinc, and aluminium are profoundly affected, resulting in occasional supply chain disruptions and price fluctuations.

Environmental Impact of Mining

While transforming into raw materials providers, miners are investing heavily in electrifying operations, deploying renewable power, and adopting zero-emission vehicles, all aimed at reducing their carbon footprint. Stricter regulations, tax incentives for green investments, and societal pressures drive this shift. In several remarkable cases, these "materials providers" became stewards of vast natural areas surrounding mining sites, guarding biodiversity, and striving to reduce CO_2 emissions. The mining industry, once seen as a polluter, is now viewed as a positive force for sustainability, equitably providing raw materials vital for clean energy while achieving ambitious decarbonisation goals. However, given economic constraints, small miners operating in developing countries struggle to obtain financing or technical expertise to implement similar upgrades. Governance and regulatory oversight remain weaker in those countries, enabling lagging polluters to continue operating. Simultaneously, global mining companies face growing expectations to ensure consistent best practices across all operations, including in developing countries.

Collaboration to close mining's pollution gap between rich and developing nations within trade blocs has grown in efforts to level the competitive playing field and promote broad sustainability. These actions are underpinned by the common, top-level goals of the major trade blocs in addressing global issues their own way but has helped keep nominal influence of international organizations as places of dialogue.

The Mining Value Chain and Mining Technologies

Market Demand for Raw Materials

The rising demand for raw materials, driven by the energy transition and the expansion of digital and energy infrastructure to support AI, quantum computing and advanced manufacturing needs, spurred mining companies to adopt strategic measures. These included expanding operations, reopening dormant mines, and adopting circular economy models to enhance production capacity.

Mineral and metal prices have surged, boosting revenues and enabling mining firms to invest in innovative technologies and community development. Research and development efforts focus on enhancing recovery rates from low-grade ores and extracting small deposits and unconventional resources, such as deep-sea, brine, deep, and urban mining. Exploration activities have also gained momentum as junior mining companies partnered with tech firms and utilised AI to discover new mineral deposits. In response to this dynamic landscape, mergers, acquisitions, and joint ventures are commonplace in the raw materials sector. These strategic actions aim for economies of scale and greater regional diversification, ensuring resilience against market fluctuations. However, challenges persist, including skill shortages, rising production costs, and community tensions, occasionally necessitating government intervention to facilitate agreements.

Full Supply Chain Tracking and Traceability of Mined Materials

Effective implementation of supply chain tracking systems to mitigate local negative environmental and human rights abuses, improve business planning, and simplify reporting for tariff systems are commonplace. This was possible due to three factors:

- Clear guidance on reporting requirements to certify minerals as "responsibly produced" or to enforce existing and future regulations related to the production and sourcing of minerals.
- Effective enforcement of existing regulations related to environmental, labour, and human rights.
- Increased consumer awareness.

Due to higher overall long-term benefits, mining communities embraced responsible resourcing and valued it above short-term direct financial benefits, leading towards a narrowing of the inequalities within blocs.

Industry Structure and Value Chain Structure

Efficiency and financial objectives drove raw materials producers to outsource non-essential functions instead of handling them

in-house. This has led to specialisation and outsourcing of non-core tasks becoming the standard in the sector. Raw materials producers frequently collaborate with various contractors for exploration, extraction/recycling, processing, and reclamation activities, often forming partnerships with Original Equipment Manufacturers. By delegating non-core activities to specialised contractors, raw materials producers now focus on:

- Managing ore deposits.
- Ensuring financial performance.
- Monitoring environmental performance.
- Building community relations.

Raw Material R&D

Developed countries are shifting toward a circular materials economy, reducing the need for primary extraction. Successful R&D applied to the raw materials sector efforts led to:

- Materials science advances enabling substitutes for rare earth elements in magnets, batteries, and electronics.
- Emphasis on urban mining, extracting metals from electronics, batteries, and vehicle waste streams, serving as a significant supplementary source of CRMs.
- Improved recycling processes, making recovery of metals highly profitable within a circular supply chain.
- Utilisation of chemical leaching, bioleaching, and nanotechnology to enhance extraction from low-grade ores and mining wastes, expanding recoverable resources.
- Advancements in tailings and landfill mining, advanced sorting, and processing of landfill deposits, reclaiming metals discarded decades ago when recycling was uneconomical.

Despite these advances, the demand for primary raw materials remains robust, driven by ongoing economic development and the energy transition.

Share of Mining in Extreme Conditions

As onshore deposits are depleted, raw materials producers turn to remote and challenging regions like African and Asian deserts, the polar regions, and deep-sea areas in the Pacific and Arctic Oceans. Technologies such as automation, robotics, AI, and remote operation make extraction feasible in these extreme environments.

Stringent environmental regulations and guidance mitigate negative mining impacts in extreme and previously pristine environments. The existing international frameworks for resolving territorial disputes have faced challenges, leading to proxy (mainly diplomatic) conflicts among major powers over access to mineral-rich regions and playing on the allegiance of less developed countries to a given bloc across continents.

Exploration

Intelligent tools have greatly boosted mining exploration productivity, relying on:

- AI algorithms and machine learning systems to analyse vast geological datasets, identifying patterns that minimised uncertainties and enhanced the likelihood of discovering mineral deposits.
- Autonomous drones and drill rigs for quicker and safer surveys and sampling in remote or hazardous areas.
- Advanced spectroscopy, 3D imaging, and sensor technology for faster sampling and geological feature analysis.
- Data from various sources consolidated into dynamic 3D models of subsurface mineral structures, accurately pinpointing drill locations.
- Real-time data during drilling for fine-tuning exploratory operations through predictive analytics, maximising the chances of hitting mineral deposits.

Increasing automation in exploration has significantly reduced costs and shortened exploration cycles, resulting in more discoveries.

Extraction and Processing Technologies

The mining industry's widespread adoption of automation and data-driven techniques increased returns. This is supported by:

- A significant boost in productivity and cost reduction across mining operations, driven by autonomous and robotic equipment, and AI-powered control systems.
- Implementation of dynamically adjusted production strategies using data analytics and digital twins, encompassing models of mineral deposits, extraction, logistics, and equipment maintenance.
- Substantial reduction in downtime through continuous operations and a sharp decline in accidents.
- Selective and optimised extraction methods targeting zero waste, resulting in higher recovery rates and economically viable extraction of low-grade ores and small deposits.
- Enhanced capacity to adjust output in response to demand, reducing price volatility.

However, the industry now faces stiff competition for digitally talented workers from other sectors.

Winners

Industry

- Tech and green innovation companies.
- Investors in sustainability assets.
- High-skilled workers specialised in emerging technologies.
- Raw materials producers supplying minerals needed for the energy transition.

Regions, Organizations, and others

- Developed countries at forefront of sustainability technologies.
- Major trading power blocs.
- Countries/regions with good geological endowments.
- Regions were mines/raw materials production centres were installed/reopened.

Loosers

Industry

- Blocs reliant on external raw materials supply chains.
- Fossil fuel sector companies and hydrocarbon-producing countries.
- Workers displaced due to automation.
- Mining companies lacking advanced capabilities.

Regions, Organizations, and others

- Poorer and developing countries lacking access to innovations.
- International organizations that are simply played by the competing blocs for political gain.

Protagonists

- Major powers; leading regional trade blocs.
- Charismatic leaders of the energy transition and tech-advancement.
- Innovators/academics of breakthrough technologies (nuclear fusion, robotics, AI).
- Regions/countries with rare/unique minerals/metals.

Disruptions

Geopolitical:

- Resurgence of multilateral cooperation and emphasis on global cooperation amid shared threats like pandemics, conflicts, or climate change.
- Reconciliation or leadership change causes reconfiguration of major blocs (e.g. U.S.-North Korea rapprochement).
- Severe tensions or conflicts between technological rivals within major blocs disrupt R&D spending and productivity.
- Armed conflict(s) beyond regional limits or directly between major players.

Economic:

- Speculative bubble bursts or extended recessions within major blocs undermine investment capital needed for ongoing innovation.
- Commodity price spikes or critical raw material supply constraints spur reconsideration of open trade policies.
- Winner-take-all dynamics concentrate gains too narrowly; popular backlash leads to policy reversals.

Social:

- Concerns over inequality and instability prompt demands for better wealth distribution systems.
- Governance reforms increase oversight and accountability for technology impacts.
- Migration flows disturb the self-sufficiency of blocs.
- Civil unrests in resource-rich, yet poorer regions.

Environmental:

- Much faster climate change impacts timeline demands urgent global cooperation.
- Critical threats in spheres like oceans, rainforests, or methane emissions override bloc differences.

Downward Spiral

Countries fall into a regressive trap in pursuit of total self-sufficiency

Rampant resource nationalism has diminished international trade and cooperation as countries turn inward to achieve self-sufficiency across energy, water, food, and raw materials production. However, the results are economically regressive and socially divisive. Restrictive policies breed constant volatility and hamper progress on issues that require shared interests like environmental standards and climate resilience, while governance capture by nationalist lobbies fosters unrest, crises of legitimacy, and active conflicts. As a result, sustainability has taken a back seat to cost considerations, ultimately culminating in widespread environmental degradation, widespread vulnerability to climate change, and policy opposition to challenging stabilization measures.

Key aspects

Rampant resource nationalism has led countries to turn inward and pursue self-sufficiency across supply chains. This regression breeds economic volatility, social divisions, and a deterioration of shared interests like environmental protection and climate resilience. To maintain control, regimes invoke nativist identities to justify crackdowns on dissent. Constantly shifting opportunistic policies foster corruption and repeated crises of legitimacy, and international cooperation and universal rights are framed as subversive ideals.

Resource-driven conflicts between major powers sparked several regional wars. Economic, political, social, religious, and cultural divides make prospects of global peace and cooperation remote. Infrastructure suffers from depressed investment and inefficient duplication across countries, severely hampering productivity. National and regional markets, prone to exaggerated demand-supply imbalances from waves of protectionism, experience extreme volatility. The resulting downturns and upcycles devastated communities and created economic distribution that fueled inequality and social unrest.

International Cooperation and Domestic Policies

- Restrictive policies hamper progress on shared interests like peacekeeping and climate resilience. Most international institutions have lost their influence and are nonfunctioning.
- Nationalist economic policies prioritise domestic self-sufficiency over global trade and cooperation. Countries vie to control entire supply chains within their borders, enacting export restrictions and barriers to international collaboration.
- The exit of foreign investors and retaliatory import taxes damage national economies, creating political turmoil and government instability across several nations, though new governments across the world persist with such inward-looking approaches.

Economic Situation

- Nativist policies exclude critical foreign investors leading to halted upgrades and maintenance of existing infrastructure, limiting long-term extraction, processing, and export capabilities across industries.
- Protectionist measures result in below-average global GDP growth as countries deviate from leveraging comparative advantages and engaging in efficient trade.
- The mining sector provides below-market capital returns due to falling domestic prices driven by slow economic growth.
- Resource nationalism drives exorbitant royalty rates and taxes and periodic nationalization creating unsustainable risk premiums and deterring investors.

Society and Environmental Aspects

- Economic crises and authoritarian crackdowns spark civil clashes, violent ideological extremism, and waves of mass migration - overwhelming remaining governance capacities. In some regions, security forces unable to maintain order give way to warlordism and paramilitary rule.
- Environmental degradation is the norm as nationalist regimes dismantled oversight bodies and suppressed activism in the race for industrial self-sufficiency.
- Oversupply within domestic markets forces mining companies to sell products at lower prices, prompting cost-cutting measures that weaken environmental and social practices, souring public opinion on mining.
- Mining firms focus on water and energy conservation due to environmental concerns and resource limitations, choosing efficiency over innovation to address the growing risks associated with water and energy supply.
- The few remaining progressive regimes retreat to climate-fortified borders, unable to mobilise regional or global cooperation on climate resilience or adaptation. All signs pointed to cascading system collapse.

The Mining Value Chain and Mining Technologies

- Regulators weaken oversight to incentivise domestic mining, concentrating environmental damage domestically which prompts battles over clean air and water in mining regions.
- Companies concerned with risk mitigation focus on efficiency improvements and maximising returns, often bypassing innovative technologies unless prompted by governments.
- Depending on risk appetite and state funding support, mining firms either seek vertical integration or outsourced activities to more risk-averse specialised players.
- Material science and mining, processing, and recycling technologies advance in some areas to improve efficiency, but trade barriers and missing global supply chains curb potential impacts on productivity.
- Unstable commodity prices, along with climbing taxes and royalty rates from resource nationalism, hamper investments in new projects and further dissuade investors.

International Cooperation and Trade

Rampant resource nationalism drives most nations to severely restrict international trade and cooperation in pursuit of economic self-sufficiency. International institutions have been hollowed out and became nonfunctional as countries prioritised narrow national interests. Global issues like peacekeeping operations, tackling climate change effects, and environmental conservation are largely abandoned in the absence of international cooperation.

Ad hoc, opportunistic alliances form between nations when short-term economic or security interests align, but these partnerships are strictly transactional and dissolve regularly with shifting political winds. The global community is fractured, and dominant military and economic powers impose their spheres of influence and arbitrary rules and standards on weaker countries.

Global institutions exist to maintain a basic level of needed coexistence and communication. Diplomacy is limited to serve nationalist agendas. Historical political and ethnic grievances spark conflicts and economic wars over resources and regional dominance. With no neutral arbiters or mediating institutions left, these conflicts exacerbate global instability.

Government Regulation and Stability of Domestic Policies

The inward economic policies implemented by most nations, like bans on exports and raw materials, punitive tariffs, and expropriation of foreign-owned industries, have backfired severely and caused intense domestic instability. While intended to capture entire supply chains domestically, these restrictive practices deter foreign investment in local infrastructure and industry. The ensuing access to limited capital creates chronic shortages and rationing. Uncertainty and xenophobia prompt remaining global firms to divest or scale down operations further in many countries, resulting in depressed productivity and technological stagnation.

Incumbent regimes have lost public faith as living standards plummet amid inflation, job losses, and shortages of critical imported goods like food, energy, and medicines. Attempts to expand domestic production capacity cannot offset vulnerabilities, as homegrown industries lack scale and reinforcements from global supply chains and trade partnerships. This fuels public dissent and a pattern of mass protests, violent government crackdowns, power seizures by authoritarian extremists, and further economic headwinds.

Economic Situation

Infrastructure

The flight of foreign investment severely constrains countries' future growth prospects. Reduced economic activity in the mining sector translates to a downward spiral with supply constraints and deteriorating infrastructure, leading to major losses of government revenues, jobs, and critical infrastructure investments. Risk-averse investors refrain from new projects and halt or cancel upgrades and maintenance to existing infrastructure. This creates a downward spiral of poor infrastructure leading to lower productivity, which further disincentivises infrastructure spending. Over the long term, severely degraded transport, power, and internet connectivity bottlenecks hamper the overall economic production capacity and export across sectors. The impact is most acute in developing countries where the extractive sector accounts for a sizable share of GDP and has multiplier effects across supply chains.

Economic Development

The wave of protectionism and the deterioration of global supply chains multiplied inefficiencies for all countries as they contorted economies to achieve self-sufficiency. Rather than focusing efforts on comparative advantages, specialisation, and mutually beneficial trade, countries expend far more resources domestically producing goods at a competitive disadvantage. This drags down both short- and long-term economic growth trajectories. Most countries' real incomes stagnate or decline over decades. The loss of economic complexity also makes countries more vulnerable to global commodity price volatility.

Price Volatility

Erratic policy shifts cause wild price swings for resources and materials within countries over short periods, creating economic chaos. Export bans initially flooded domestic markets with minerals, metals, and other commodities, depressing prices as homegrown processing capacity is limited. In response, miners throttle production, setting up the next supply crunch when export bans shift again. Countries that restrict exports of key inputs see drastic price spikes and shortages for domestic manufacturers. These violent boom-bust cycles handicap businesses, disrupt supply chains, and hammer household budgets and the socio-economic fabric.

Economic Situation

Profit

Unstable and plummeting commodity prices combine with creeping resource nationalism to severely impact mining profitability. Governments seek higher shares of mining revenue through increased royalties, taxes, and threats of expropriation to close growing budget gaps. This toxic policy climate disincentivises investors seeking market-rate returns, deplete capital for new projects and technology upgrades, and drag the entire sector into a long-term productivity decline relative to the overall economy. The extractive industry became synonymous with country risk and confiscatory regimes. Only the most risk-tolerant investors remain active in the space.

Society and Environmental Aspects

Responsible Consumption and Production & Social Attitude towards Mining, Public Acceptance

The public soured on the mining industry as the negative impacts of unchecked extraction piled up within countries pursuing self-sufficiency. With export markets closed, miners flood domestic commodity markets, depressing prices below profitability levels. Many cut costs by rolling back environmental and community investments and abandoned social license efforts. Health and pollution externalities are passed on to the public as oversight has faded. After experiencing first-hand the abusive practices enabled by resource nationalism, public attitudes towards mining worsen markedly over time despite initial nationalist-driven fervour.

Integrated Climate Action

Domestic mining policies oppose widescale changes that would transform carbon-intensive conventional practices, instead only permitting incremental efficiency improvements that result a status quo reliance on fossil fuels. Without concerted climate policies or international collaboration driving demand for low-carbon minerals, most mining does little to enable the energy transition. Renewables and electric vehicles remain niche. While miners make some site-level adaptations to climate risks in vulnerable regions, they play no role in developing mitigation or carbon removal technologies at scale.

Water and Energy Strategies

With mining productivity and recycling practices handicapped by economic policies, most companies retrenched around low risk conventional deposits. Exposure to water stress and energy poverty increased. Periodic shutdowns or output cuts became commonplace as local community needs clashed with industrial usage. Most adaptation measures focused on improving efficiency and conservation driven by cost control rather than systemic resilience to intensifying climate impacts. Even major investments couldn't offset the underlying vulnerability of mining operations in water-scarce, energy-poor regions once considered fringe. Supply disruptions from climate disasters became common.

Environmental Impact of Mining

Government incentives around raw materials production cluster extraction and processing geographically, overburdening particular communities to achieve domestic self-sufficiency aims. Remote and mineral-rich areas see environmental standards weakened to support needed industrial growth. Some domestic clusters of mines and recycling centres benefit from government support for infrastructure, processing hubs, specialised services, and captured economies of scale. However, these clusters also result in pollution accumulating to extreme levels with little recourse for local communities suffering health effects and loss of traditional livelihoods. With oversight gutted everywhere, environmental disasters occur more frequently, even in developed regions.

The Mining Value Chain and Mining Technologies

Market Demand for Raw Materials

Ongoing global economic weakness and extreme commodity price volatility depresses demand for raw materials. Existing miners and recyclers focus on cost-cutting and operational efficiency rather than expanding production or investing in new capacity. Many high-cost mines are shuttered, removing their supply and potential capital from the economy. Material intensity per GDP stalls worldwide. Modest growth remains confined to developing countries and regions tapping local mineral resources out of necessity to fuel industrial self-sufficiency drives, though output lags badly on costs. Clean energy remains a niche without climate policies. Extraction activity contracts overall from peak levels.

Industry Structure and Value Chain Structure

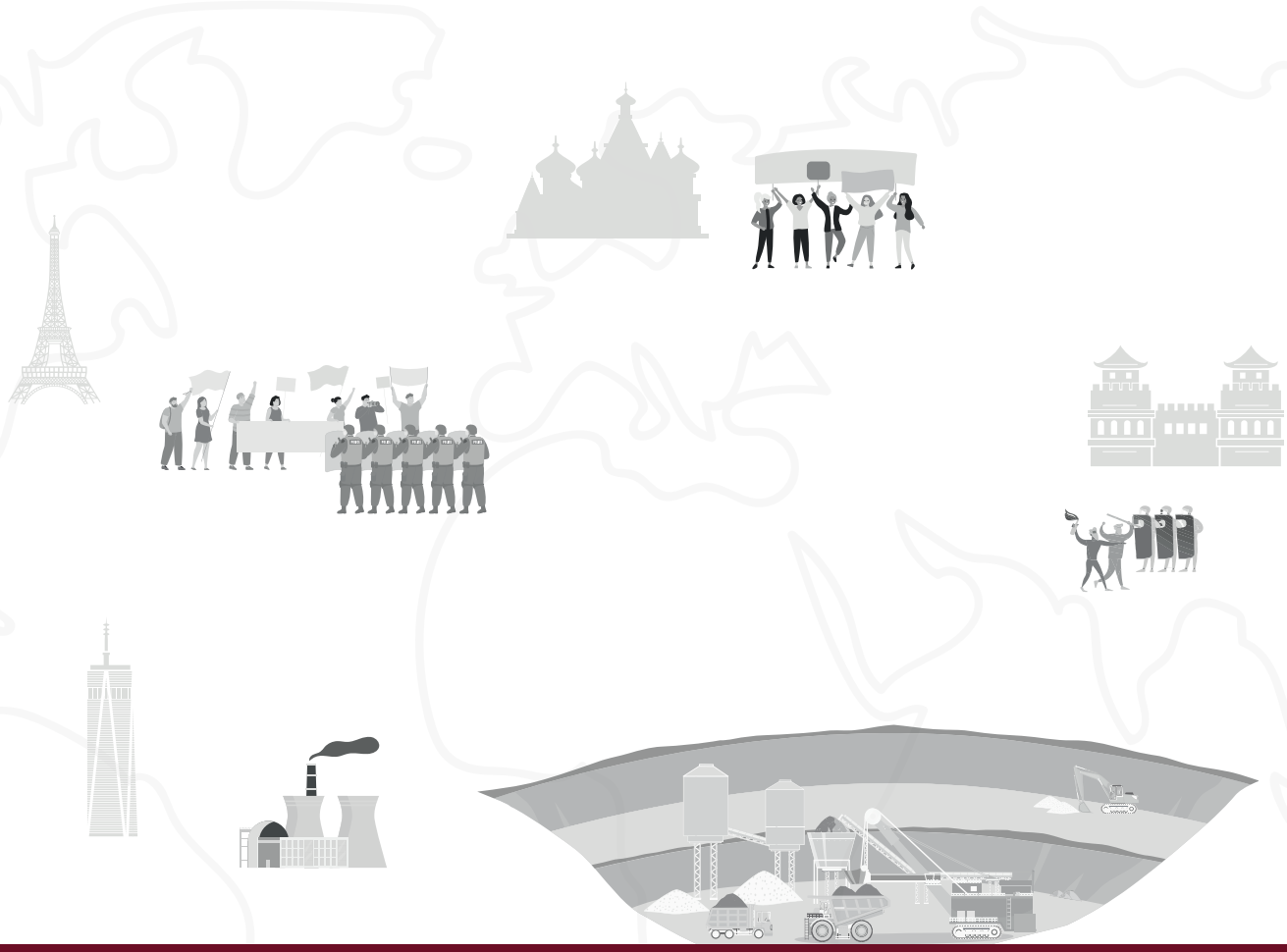
Many miners pursue vertical integration into domestic transportation, processing, and manufacturing to bypass export barriers. But with only localised end-markets, overinvestment and underproduction is common and periodically supported by government subsidies to ensure basic sourcing. When self-sufficiency policies fail to deliver expected demand growth, low commodity prices make these capital-intensive facilities unprofitable. Shareholder pressure pushes majors to focus on efficient mining while offloading processing assets to specialised domestic firms better equipped to handle market volatility in smaller niches. The rise of flexible niche players offsets tendencies toward complete vertical integration.

Exploration, Share of Mining in Extreme Conditions, and Extraction Technologies

Developed and developing countries follow different paths around mining productivity. Advanced economies leverage technologies like AI, remote operation, remote sensing, and automation to unlock new deposits and sustain output despite high costs. Their expertise allows economic access to ever more extreme locations previously out of reach. Poorer but resource-rich countries remained trapped, relying on cheap labour with only incremental innovations available locally. Extraction technologies have bifurcated, based on national capabilities and government support.

R&D

To bypass reliance on imports, governments fund basic research into substituting imported critical raw materials across defence, technology, and manufacturing applications with accessible materials. However, depressed economic conditions ensure only minimal resources redirected from immediate needs, and the lack of international collaboration causes duplication of effort. Technology advancements slow below their potential, handicapping industrial development.



Winners

Industry

- Risk-averse, internally well-capitalized mining companies (sometimes with government backing) willing to invest in rich countries and vertically integrating (or willing to provide specialized services in the form of infrastructure investments or processing plants).
- Companies with capacity to leverage advanced exploration and mining techniques.
- Domestic mining and processing companies that align interests with ruling regimes.
- Black market smugglers and illegal mining networks dealing in materials scarce in domestic markets.

Regions, Organizations, and others

- Resource-rich countries (short-term).
- National/Regional financial institutions with very focused and specialised investment goals.
- Authoritarian regimes and nationalist extremists who exploit economic turmoil and social unrest to expand their power.
- Powerful countries with large domestic markets, resources, and advanced technologies to pursue self-sufficiency.
- Private military contractors and security firms that profit from conflicts and instability.

Loosers

Industry

- Mining companies operating in countries with an export ban (short-term).
- Foreign investors who invested in a country prior to the rise of resource nationalism and introduction of export bans and tariffs.
- Tourism.
- Most mining and materials companies with limited internal capital and/or inflexible business strategies unable to operate profitably amid volatile conditions.

Regions, Organizations, and others

- Countries lacking resources or capabilities that can approximate self-sufficiency.
- Countries heavily reliant on trade and global supply chains for economic growth.
- Citizens and local communities impacted by concentrated environmental damage and pollution.
- Marginalised ethnic groups scapegoated for economic troubles.
- International institutions, NGOs, human rights, and environmental activists.
- General public enduring restrictions, shortages, inflation, and depressed real standards of living.

Protagonists

- Technology companies.
- Authoritarian and nationalist governments.
- Powerful, state-owned raw materials producers.
- Black market networks.
- Security services and military forces.
- Insurgent groups and extremist organisations.

Disruptions

Geopolitical:

- Collapse in rule of law, allowing criminal networks to overwhelm state authorities, and collapse of residual capital flow.
- Radical extremist factions overthrowing nationalist governments.
- Emergence of more liberal internationalist successor generations within closed regimes.
- Significant disruption in major powers leading to external geopolitical realignments.
- Transnational activist cyber-attack crumpling industrial systems infrastructure.

Economic:

- Breakthroughs in renewable energy, batteries or carbon capture lowering demand/prices for mined commodities.
- Revolution in materials science lowering needs for contested rare-earth minerals.
- Unforeseen technology innovations (AI, synthetic biology, clean fusion, etc.) disrupting production.

Social:

- Mass organised labour strikes or middle-class protests within authoritarian countries.
- Ethnic insurgencies or civil wars inside resource-rich failed states.
- Global pandemic or food system crisis exacerbating migration and instability.

Environmental:

- Watershed ecological/climate disaster events spurring emergency cooperation.

The Great Transition

A global crisis sparks unprecedented unity

A global catastrophe shocked the world by putting humanity at risk, but out of the ashes arose a societal metamorphosis driven by strong leadership that yielded unprecedented unity to rapidly transform social and economic systems into a sustainable, circular, shared-prosperity paradigm focused on people and stewardship of our planet catalysed by drastic changes to the energy, food, and raw materials systems.

Key aspects

In the late 2020s, civilisation faced a global catastrophe that occurred as critical international organizations were particularly ineffective in coordinating global consensus and response, leading to retreats in global economic and social activity. In the following decade, the event brought together countries and blocs with previously divergent interests to address common challenges facing humanity. Society realised that to ensure survival, humanity needed to confront environmental, social, technological, and industrial challenges together. A successor to the UN, The Global Council of Nations (GCN), is established and led coordination and policy frameworks during the initial recovery until global cooperative efforts became pervasive. A new generation of visionary, inspirational, and charismatic political leaders pushed reforms focused on increasing sustainability sparking new energy, food, and raw materials production technologies. GCN summits and working groups enabled multilateral agreements and knowledge sharing vital to the rapid adoption of new technologies and practices across borders. The circular economy, and the use of green technologies, have become the standard in most parts of the world, including many developing countries. Except for a few isolated countries, humanity is in a new age based on universal prosperity and the planet's well-being.

International Cooperation and Domestic Policies

- The new Global Council of Nations enabled unprecedented cooperation between formerly divergent countries and blocs to confront shared challenges.
- Nations realised the critical need to subordinate narrow self-interests for the greater good.
- Multilateral governing bodies effectively coordinated economic and social policies that benefit climate goals and sustainability reforms across borders.

Economic Situation

- Sustainability is recognised as the ultimate economic priority. This both enabled the availability of goods for developed countries and improved the prosperity and socio-economic development of developing countries.
- Incentives, taxes, and regulations to accelerate decarbonisation and circularity is harmonized among nations.
- With strong, coordinated public infrastructure investments, low inflation, and policy stability, private capital is focused on green technologies, unleashing an innovation boom.
- Free trade policies are dominant and effective technology-transfer processes developed towards supporting a sustainable and thriving global society.

Society and Environmental Aspects

- People fully recognizes that growth and a thriving society is built on cooperative advancement for all rather than short-term zero-sum games.
- Income stratification has eased with the rising tide of equitable green growth, especially in access to energy, water, and safety.
- Grassroot movements and enlightened industries have driven adoption of responsible, ethical practices benefiting people and nature. Widely adopted standards of responsible consumption and production and high social standards are implemented in the industry, which led to increased public acceptance of mining.
- The mining industry contributes to climate actions with conservation efforts of water and energy and reduces pollution to a minimum level.

The Mining Value Chain and Mining Technologies

- Advanced technologies have enabled the discovery and precise extraction of minerals essential for sustainable infrastructure.
- Automation has improved productivity and safety.
- Recycling and circularity have minimised the need for new mining.
- Radical transparency verified high ESG standards through supply chain tracking leading to restored public trust in the mining industry.

International Cooperation and Trade

After the global catastrophe and years of devastation and scarcity, the newly created Global Council of Nations fostered unprecedented cooperation, enabling the free flow of knowledge, technologies, and raw materials to accelerate both economic and social transitions to sustainability. Goods and raw materials are traded freely, yet responsibly, under cooperative accords upholding ethical and environmental standards. With political stability and aligned interests, strong interregional supply chains thrive which has unleashed innovation. Occasional attempts to form trade blocs fail to overtake the global free trade momentum and quickly faded away. Resource availability is viewed in a global lens, especially as the equitable access to resources accelerated material demand from developing nations. Global trade agreements ensured ready access and non-discriminatory policies on trade.

Stability of Domestic Policies

Unity behind the shared vision of sustainable prosperity has yielded domestic policy continuity over time, both within administration durations and election cycles. This long-term policy predictability nurtures private sector confidence to fund projects with decadal horizons. Resource nationalism has faded as raw materials' access has become more equitable and governance more transparent, allowing domestic and global trade needs to be met across nations. Lower investment risks spur capital availability even with narrowed margins and interest rates.

Government Regulation

While specific permitting processes vary, the Global Council of Nations promotes model frameworks balancing efficiency with environmental stewardship. Streamlined approvals have enabled essential projects to come online quickly, while centralised data and supportive development banks ease investor access, compliance, and assurance with governments becoming constructive partners in sustainable development of mineral resources. With cooperation trumping conflict, the pace of responsible resource extraction has accelerated across the world.

Economic Situation

Economic Development

Following the global catastrophe and the ensuing sharp global economic contraction, the world economy experienced an era of remarkable expansion and renewed vitality through the combination of substantial global redevelopment, low-cost energy, and multilateral trade agreements prioritising collective well-being over isolated interests. This dynamic also reduced focus on short-term capital returns, fostering investment in long-term projects. This catalysed a robust and well-distributed growth in GDP, lifting developing nations to begin catching up to the developed world. The synergy of demographic shifts in developing regions, namely less emigration once a critical level of economic opportunity arose domestically, and the burgeoning intellectual capacity worldwide has fostered an environment conducive to economic growth driving ongoing infrastructure development. This growth has spiked the demand for essential materials such as iron, aluminium, copper, cement, and construction aggregates. Concurrently, the global commitment to sustainable practices and decarbonisation has spurred a heightened demand for advanced consumer electronics and green technology, providing a lucrative market for companies specialising in essential raw materials for these industries.

Infrastructure

The post-catastrophe era drove substantial infrastructure investments, including the development of new roads, railways, and ports, effectively connecting remote mining areas with major export centres. These investments extended beyond mining, encompassing power generation, water management, and digital connectivity, thereby lifting local living standards from the resulting regional economic development. Additionally, many developing nations benefited from infrastructure support provided by more developed countries through bilateral cooperation and trade agreements. These partnerships often included provisions for local processing of raw materials, thereby increasing local value addition and expanding the economic impact for sustainable economic activity.

Price Volatility

The 2050 economic climate is characterised by low and stable commodity prices, prompting mining and recycling companies to prioritise investing in efficiency and technological innovation, including automation and robotics, over the risk aversion from boom-and-bust cycles. This environment has discouraged overexpansion and fostered a focus on sustainable growth driven by real demand. Consequently, commodity providers in 2050 plan for long-term investments and operations, rather than reacting

to short-term market fluctuations. This strategic approach, coupled with industry consolidation through mergers and joint ventures, has enabled economies of scale and optimised exploitation of high-quality primary and secondary deposits.

Profit

The consensus on sustainability and the green transition significantly amplified demand for minerals critical to clean energy technologies. Recognising the long-term scarcity of many raw materials, governments worldwide have streamlined permitting processes and invested in infrastructure. Advances in technology, particularly in robotic extraction methods, enable efficient exploitation of smaller high-grade deposits, leading to optimised sector performance, reduced capital costs, and enhanced productivity. These factors have made the mining sector in 2050 an attractive avenue for investment, especially with a renewed focus on long-term returns, with substantial and stable returns on capital, especially in the production of critical and strategic minerals.

Society and Environmental Aspects

Social Attitude towards Mining, Public Acceptance

The global consensus on the green transition and widespread adoption of decarbonisation policies significantly increased demand for minerals critical to clean-energy technologies. Recognising the long-term scarcity of many raw materials, governments worldwide streamlined permitting processes and invested in supporting infrastructure. Technological advances like robotic extraction are driving more efficient and sustainable exploitation of deposits. These factors have made mining an important avenue for investment and economic development focused on sustainability and prosperity for all, especially in the developed world. Developing nations continue to seek direct economic benefits like employment, and thus are slower in adopting the most advanced technologies until they begin to see aggregate national economic growth beyond the resource sector. Mining is now viewed by the public as an essential sector supporting the continued transition to renewable energy and a circular economy. Surveys in 2050 show substantial improvement of public perception of the mining sector, especially related to sustainability, compared to the past decades.

Mining Workforce

More mining companies now also provide raw material recycling and work closely with communities for economic inclusion and climate resilience. This has improved public perception and attracted more talented youth to pursue educational pathways leading to mining-related employment. However, skilled labour demand continues to outpace supply though the high-quality workforce pool emerging after 2040 narrowed the gap. Enrolment in materials engineering, mining engineering, and geology programmes has risen globally. As global population growth continues to slow with dropping birth rates even in developing nations in response to their improved economic situation, automation advancements have not offset all labour needs. In particular, the scientific and engineering problems faced by the mining industry continued to get more challenging, thus making well-educated and skilled labour an increasing necessity while alleviating short-term pressures with each new technology advancement. Slowing population growth that started in the 2020s has led to constrained labour markets with more intense competition between sectors, making even the lower retirement rates relative to the 2020's and early 2030s still exceed graduation rates for critical roles like mine planning engineers.

Water and Energy Strategies

Addressing environmental impacts and community needs led firms to shift attention from water-stressed, energy-scarce locations towards sites with fewer natural resource limitations. However, the increasingly common extreme weather events impact commodity availability, causing supply chain disruptions. In 2050, miners now routinely conduct climate vulnerability assessments to model and mitigate supply chain risks. Most large commodity providers are committed to achieving net zero emission targets through the adoption of renewable energy and process efficiencies. Microgrid technologies enabled effective utilisation of solar, wind or hydro resources proximal to operations around the world.

Integrated Climate Action

In addition to increasing the output of crucial metals like lithium and cobalt, stable investments enabled firms to reduce carbon footprints by electrifying operations, utilising renewable energy, and adopting zero-emission vehicles, thus effectively reducing the carbon footprint of global expansion of electrification. Moreover, energy-intensive processes are increasingly rare as the industry prioritised sustainability.

Responsible Consumption and Production

Widely adopted standards for responsible production, certification schemes, and tax incentives promote low-carbon, sustainable mining practices throughout the global supply chain. Most sustainability-conscious consumers seek products utilizing responsibly produced raw materials, positively impacting markets. Multiple global frameworks cover environmental and social issues at all lifecycle stages. Responsible Production certifications are now required by major manufacturers in the transportation and electronics supply chains. The ability for developing nations to meet the rigorous requirements has been a predictor for their economic growth rate.

Environmental Impact of Mining

Although sustainable technologies have enabled progress in developed countries and large companies, smaller miners in developing nations lack access to financing and/or expertise to implement similar upgrades, given economic constraints and regulatory gaps. However, collaborative efforts to close these gaps have grown in importance for broad sustainability. The Global Council of Nations, industry groups, and NGOs have global programmes to assist small-scale miners in emerging economies with adopting cleaner practices through grants and technical partnerships.

The Mining Value Chain and Mining Technologies

Market Demand for Raw Materials

The surge in demand for raw materials led mining companies and recyclers to expand operations, reopen closed mines, and initiate new projects to boost production. Steady and market-balanced mineral and metal prices increased revenues, enabling investment in innovative technologies and community development to increase long-term margins. Western governments have eased regulations, particularly in less populated areas, to expedite investment. Research and development in technologies for extracting from low-grade ores and unconventional resources, like deep-sea and urban mining, continue. The rate of exploration has intensified with junior miners using AI and collaborating with tech providers create an entire new facet of the mining industry. As with all periods of change, the industry experiences many mergers, acquisitions, and joint ventures to improve scale and asset diversity. Still, challenges like skill shortages, local community tensions, and higher production costs do arise. Introduction of mining process automation has reduced aggregate labour requirements while also changing the needed labour portfolio. Community engagement strategies were implemented to improve alignment of the emerging labour supply.

Full Supply Chain Tracking and Traceability of Mined Materials

Supply chain tracking addresses concerns on environmental and human rights issues, aided business planning, and simplified reporting. Acceptance of tracking was enabled by clear guidelines for certifying responsible production, consistently enforced regulations, and growing consumer awareness and willingness to pay for ethical sourcing. Blockchain and IoT technologies allow real-time monitoring to trace metals back to origin mines or recyclers. Developing nations that actively engaged in traceability efforts have experienced more rapid economic returns and increased global political and economic leverage.

Industry Structure and Value Chain Structure

Specialisation superseded vertical integration, as miners and recyclers increasingly outsourced non-core functions to contractors and OEM partnerships focused on efficiency and addressing chronic labour supply challenges. By concentrating on orebody/resource management, financials, monitoring, and community relations while leveraging third-party expertise in exploration, extraction, processing and reclamation, mining and recycling companies have enhanced overall industry performance.

Raw Material R&D

Developed countries operate in a relatively more circular materials economy, reducing demand for primary material extraction, thanks to R&D in recycling and CRM substitution. Critical breakthroughs have included substitutes for rare earth elements in key technologies, urban mining of electronic waste, and profitable metal recycling processes like lithium and cobalt recovery. Techniques, like chemical leaching and nanotechnology, improved extraction from low-grade ores and waste are also critical improvements. In 2050, landfill mining is reclaiming previously unusable metals. Despite these advances in non-virgin recovery, ongoing global economic development continues to drive strong demand for primary raw materials.

Share of Mining in Extreme Conditions

Miners have turned to remote areas like African and Asian deserts, the polar regions, and deep-sea regions for untapped mineral deposits as new traditional onshore resources dwindled. Advanced technologies like automation, AI, and robotics make mining in these extreme environments economically feasible. Supply chains have evolved, favouring developing countries and

adapting to these new locations, especially those that adopted methodologies to meet supply chain monitoring. Although comprehensive environmental regulations exist, enforcement remains variable with reported malpractices particularly among more traditional enterprises. Territorial disputes and proxy wars over resource-rich areas still occur, challenging international frameworks, but global pressure for stability help global institutions limit the impact of these conflicts. Still, this expansion spurred innovations in robotics, remote operations, and materials engineering, benefiting various industries.

Exploration

Intelligent tools have significantly boosted mining exploration productivity by leveraging AI and machine learning for analysing extensive geological data and thus increasing mineral discoveries. Key advancements included autonomous drones and drill rigs for efficient, safe surveys in remote areas, and cutting-edge spectroscopy, 3D imaging, and sensor technologies for rapid sample analysis. Comprehensive 3D subsurface models are created from aggregated data, accurately guiding drilling decisions. Additionally, real-time data during drilling enhances exploratory operations through predictive analytics. The increase in exploration automation has notably reduced costs and cycle times, resulting in more frequent discoveries. Additionally, these less intrusive techniques allow better community engagement about projects with well-defined goals and returns, especially in areas historically sceptical or previously impacted negatively by mining, thus decreasing the social risk of investments.

Extraction Technologies

The mining industry's adoption of automation and data-driven techniques significantly improved returns by:

- Increasing productivity and reduced costs via autonomous vehicles, robotic equipment, and AI control systems.
- Utilising data analytics and digital twins for dynamic production strategies, encompassing mineral deposits, extraction, processing, logistics, and equipment maintenance.
- Decreasing downtime through continuous operations, which lead to fewer hazards and accidents.
- Implementing selective extraction methods for zero waste which enables economical mining of low-grade ores and small deposits.
- Adjusting output in response to demand and thus managing price volatility.

The industry faces a skills shortage and competition for digitally skilled workers, which is especially fierce in traditional mining communities, as highly efficient mines require fewer but more highly qualified, and thus compensated, workers. Still, optimised techniques have enabled viable extraction of low-grade ores and small deposits with minimised environmental impacts.

Winners

Industry

- Major diversified mining companies benefit from demand growth due to financial strength, economies of scale, technology access, and partnerships.
- Specialised technology/services providers via partnerships with miners in areas like automation, AI, exploration, processing, etc.
- Smaller mining players, flexible enough to adapt to stricter standards.
- Tech and green innovation companies.
- Investors in sustainability assets.
- High-skilled workers specialised in emerging technologies.

Regions, Organizations, and others

- Developing Countries and regions with previously untapped resources.
- Future generations and society.
- International organisations, responsible for treaties and agreements implementation and application.

Loosers

Industry

- Mining companies, no matter the size, unable to adapt to prevailing industry standards for responsible production.
- Mining companies, no matter the size, reliant on older processes and technologies.
- Workers unable to adapt to new technologies.

Regions, Organizations, and others

- Regions unable to adapt to new standards.
- "Solo players" in an open global market.
- Mining-dependent communities without economic alternatives impacted by lower aggregate demand for workers.

Protagonists

- International organisations and multi-stakeholder groups, facilitating broad diffusion of sustainability frameworks, knowledge sharing and consensus building.
- Visionary political leaders, driving reforms, investments and multilateral coordination focused on sustainability and prosperity.
- Countries and regions affected by the global catastrophe.
- Governments of resource-rich regions / countries.
- Consumers/society.

Disruptions

Geopolitical:

- A status quo approach that puts society in a state of passive survival, but not shocking enough to cause dramatic political unrest and global change.
- Partial export limitation of major commodities by one country or a bloc of countries resulting in a gradual and long-term CRM (Critical Raw Materials) availability shortage.
- Developing nations capable of integrating into global sustainability and governance frameworks can exercise new influence into a consumption-defined system by leveraging their newly found producer-based power.

Economic:

- Partial export limitation of major commodities affecting CRM availability.
- Economic fluctuations are regularly present, but not detrimental enough to result in market and economy collapse.
- No notable advances in technology due to the discovery of huge resource deposits in remote areas.

Social:

- Society accepts that natural disasters and wars have been a humanity companion for millennia and accepts the frequency of these events, thus weakening the newly robust international organizations.
- Status quo puts society in a state of passive survival, but not shocking enough to cause dramatic political unrest.
- Scarcity of water and energy resources, combined with climate changes, is manageable. People survive and move on despite shortages and disasters without major noticeable disruptions that cause major losses or climate refugee movements.

Environmental:

- Combined with climate changes, the scarcity of water and energy resources is manageable.
- No notable advances in technology due to the discovery of huge resource deposits in polar areas.

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