In collaboration
with Kearney

WORLD
ECONOMIC
FORUM

From Minerals to Megawatts: Building Resilience for EVs, Data Centres and Power Grids

WHITE PAPER

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Images: Getty Images

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Foreword

Kiva Allgood
Managing Director, World Economic Forum

Jonathan Price
President and Chief Executive Officer, Teck Resources

Jeremy Weir
Chairman, Trafigura Group

Igor Hulak
Partner and Global Head of Mining and Metals, Kearney

The race to electrify, digitalize and decarbonize the global economy relies on resilient, transparent and sustainable minerals and metals supply chains – building the foundation on which both today's global economy and the ongoing energy and digital transition rest.

Yet these complex supply chains face increasing strain: they span continents, operate on long permitting timelines and remain highly concentrated in a small number of regions. Meanwhile, global demand centres are shifting rapidly – from the accelerating pace of industrial activity to the unprecedented build-out of electricity systems, data centres and clean-energy infrastructure. Together, these pressures create systemic vulnerabilities that can disrupt everything from infrastructure delivery to industrial competitiveness.

To confront these challenges, the World Economic Forum, in collaboration with Kearney and with support from the Forum's Mining and Metals Industry Community, has developed this focused work stream under the Future-Proofing Global Value Chains initiative to build awareness and outline practical collective actions for strengthening resilience in the minerals and metals supply chains across electric vehicles (EVs), data centres and grid infrastructure.

Governments, companies and investors each have a role to play in streamlining permitting, scaling secondary and circular supply, strengthening platforms for ongoing dialogue and creating shared accountability. Meaningful progress will also depend on deeper coordination with the global public-sector leaders who shape policy, infrastructure planning and long-term investment signals. Achieving this calls for structured collaboration across sectors, industries and regions at a scale not seen before.

Although collaboration across regions and sectors has long existed, its nature is evolving. Today, regional alliances, cross-value chain partnerships and public-private platforms are moving beyond dialogue and compliance towards more integrated, data-driven ways of working that can drive progress at multiple levels. When connected through common standards, shared data and mutual recognition, these local and regional efforts can reinforce one another and strengthen the resilience of the overall system.

Driving this type of coordinated action requires creating the conditions for actors to align on shared priorities and timelines, each within their scope. Initiatives that convene diverse stakeholders, foster knowledge exchange and align incentives can transform fragmented efforts into tangible progress. These actions will be essential as we elevate this resilience agenda across value chains.

If we act together, we can future-proof global value chains and ensure that the materials essential to the energy transition and other systemic global transformations are delivered reliably, responsibly and at the scale the world demands.

Executive summary

The resilience of the minerals supply chains that underpin electrification and digitalization depends on structured multistakeholder coordination.

The pace and scale of electrification and digitalization depend on resilient, transparent and well-coordinated minerals and metals supply chains. Electric vehicles (EVs), data centres and electricity transmission and distribution (ET&D) each rely on the same materials, such as copper, aluminium and rare earth elements. These are processed through a small number of refining hubs, making resilience a shared priority for industry and government.

Yet, the system remains only partially understood. Interconnections and vulnerabilities across value chains run deeper than many stakeholders realize. Shared refining hubs and common upstream bottlenecks mean that a disruption in one sector can reverberate across many others. These links, however, are rarely reflected in systemic or coordinated policy decisions – many recent measures address minerals supply and security in isolation rather than as part of an integrated value-chain approach. Early warning signs are already apparent: new capacity for critical minerals remains unpermitted or unfunded, while demand continues to outpace upstream investment.

Against this backdrop, the World Economic Forum, in collaboration with Kearney and enabled by the support of the Forum's Mining and Metals Industry Community, consulted with more than 65 senior executives across these value chains to hear their perspectives and shape a shared understanding of the issues. These are captured in this white paper, which aims to:

1. **Clarify interdependencies:** Show how mineral dependencies connect sectors that were once thought of as distinct. EVs, grids and data centres rely on many of the same materials and refining and manufacturing hubs, yet decisions are still taken in silos (Sections 1-2).
2. **Strengthen shared awareness:** Identify where vulnerabilities lie, how technology and policy shifts shape demand and why fragmented responses amplify risk (Section 3).
3. **Drive collective actions:** Emphasize that coordination across supply chains, investment timelines and policy frameworks is essential to manage these risks and ensure capacity grows where and when it is needed (Section 4).

Resilience will not emerge organically. It requires structured collaboration – connecting decisions, priorities and investment timelines across industries, financiers and governments. Progress will depend on empowered coordination platforms and partnerships, capable of convening diverse actors and aligning their efforts towards shared outcomes.

Building on findings from the Forum's Securing Minerals for the Energy Transition (SMET) initiative, this paper outlines four key building blocks for collective action to translate collaboration into tangible progress:

- Strengthen coordination mechanisms to bring together stakeholders and align priorities across sectors.
- Build a shared risk picture to clarify vulnerabilities, bottlenecks and interdependencies.
- Deploy collective resilience strategies – combining supply diversification and expansion with demand-side measures.
- Enable collaboration through convening platforms, transparency tools and common standards.

This decade will be decisive for the energy and digital transformations already underway. Delivering vehicles, data capacity and grid infrastructure on time to meet the pace and scale of these transitions will depend on multistakeholder coordination – anchored in shared awareness of the mineral systems that connect them all.

1 Understanding mineral intensity

Resilient mineral supply chains will determine how fast electrification, digital infrastructure and global competitiveness can scale.

Understanding how mineral reliance connects these interdependent systems is the first step towards building resilience. EVs, data centres and ET&D underpin modern economies and daily life. Each drives electrification and digitalization, relying on overlapping materials, suppliers, refining capacities and interdependent systems.

Batteries, semiconductors and transformers rely on overlapping refining and manufacturing hubs concentrated in a few countries. EVs charge on the grid; data centres use the grid to operate; the grid needs a steady flow of transformers, cables and power electronics; and global value chains depend on data. Recognizing these interdependencies is essential for effective planning and coordinated action.

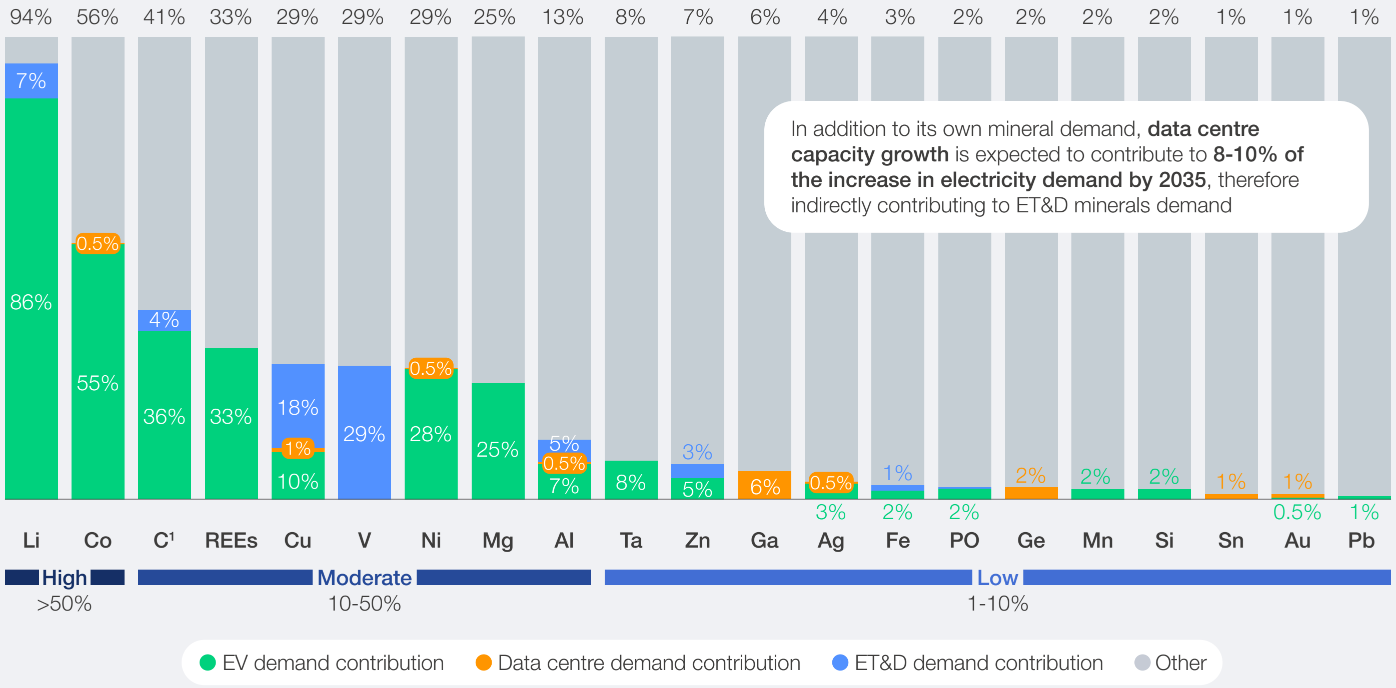
FIGURE 1 **Overview of growth trajectory, and minerals and metals used for select value chains**

Note: Based on International Energy Agency (IEA) announced pledges scenario
Sources: S&P Global, IEA,[1] Bank of America Securities,[2] Bloomberg, Kearney analysis

Mineral intensity has two aspects: scale and criticality. Sectors with a large share of global demand – such as EVs for lithium, and grids for copper and vanadium – can shape market signals, steer investment and accelerate innovation, but are also mutually exposed to vulnerabilities faced by producers that, in turn, rely on their bankable demand to scale capacity.

Sectors with smaller demand have many essential specialty inputs – such as data centres' reliance on gallium, germanium and rare earth elements (REEs) – yet have limited sway over supply or policy decisions and must track the moves of bigger buyers. Figure 2 shows why both groups need to engage: those with scale influence outcomes; those with critical need feel the consequences.

FIGURE 2 **Value chain demand contribution across tracked minerals** (% of total global demand, 2035e)



In addition to its own mineral demand, **data centre capacity growth** is expected to contribute to **8-10% of the increase in electricity demand by 2035**, therefore indirectly contributing to ET&D minerals demand

Note: ¹C: Graphite

Sources: IEA, Shanghai Metals Market, CRU, Association for Iron & Steel Technology, International Lead and Zinc Study Group, United States Geological Survey, Silver Institute, Research and Markets, International Tin Association, S&P Global and Kearney analysis

The next three subsections map where minerals sit inside each product system.

1.1 The known frontier of electric mobility

Industry consultations and extensive literature review reflect broad awareness that EVs are highly mineral-intensive. By 2035, EVs are projected to account for 86% of total lithium demand, 55% of cobalt and one-third of global rare-earth consumption, placing their supply chains at the centre of future mineral balances.

The following breakdown illustrates how key EV components translate into distinct minerals' demand, each shaping exposure and supply dependencies differently.

Battery pack

Batteries are a key driver of EV mineral demand. Two cathode chemistries dominate: nickel-manganese-cobalt (NMC) and lithium-iron-phosphate (LFP). Chemistry choices shape EV cost and performance and the geographic footprint of upstream refining and processing, with the shift towards LFP reducing reliance on cobalt and nickel.

Motor

Traction motors and associated power electronics, while relatively small in mass, add another layer of material exposure. Permanent-magnet motors rely on REEs such as neodymium (Nd) and dysprosium (Dy), alongside copper in windings and busbars.

Wiring and power electronics

Power electronics and wiring make EVs significantly more copper-intensive than internal combustion engine (ICE) vehicles, with aluminium substitutions in some designs where standards allow and dependence on silicon and emerging silicon-carbide (SiC) semiconductors, whose specialized manufacturing capacity is tight against rising demand.

Structure (chassis and body)

Metal mass in EVs is dominated by steel and aluminium. These are mature, globally traded metals with established recycling flows, but their scale makes them production-critical.

Trend: Evolving battery chemistries, motor designs and power electronics are reshaping material demand across EV value chains – reducing reliance on cobalt and nickel through LFP adoption, raising copper and semiconductor needs through electrification of drivetrains and increasing aluminium use through light-weighting and megacast structures.[3]

FIGURE 3 | **EV component breakdown by mineral (kgs per vehicle)**

Total minerals and metals mass in passenger EVs: ~900-1000kg

EV wiring and power electronics
~3-4% of minerals and metals used in EV

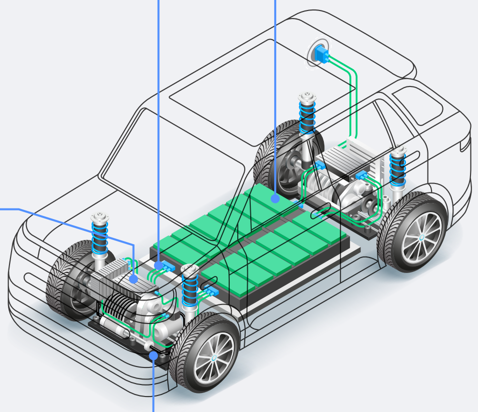
Copper	~27
Aluminium	~3
Gold	<0.1
Silicon	<0.1
Silver	<0.1
Tin	~0.2
Tantalum	<0.1

EV motor
~2-4% of minerals and metals used in EV

Rare earths	~0.7
Steel	~20
Copper	~7
Aluminium	~1.4

Structure (chassis and body)
~50-65% of minerals and metals used in EV

Steel	~385
Aluminium	~145
Magnesium	~8
Zinc	~12



EV battery pack
~30-40% of minerals and metals used in EV

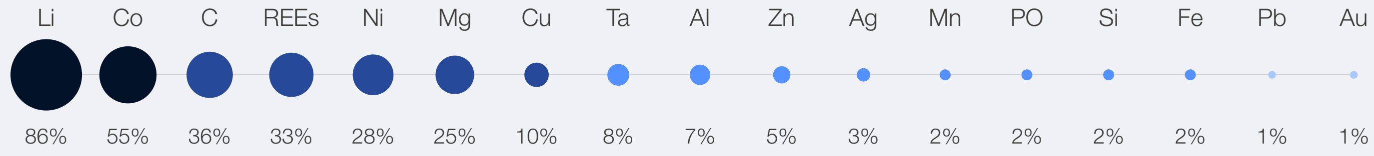
Graphite	~40
Silicon	~1
Aluminium	~30
Copper	~20
Steel	~20

Cathode chemistry	High nickel	Low/mid nickel	LFP	High manganese	Sodium-ion
Lithium	~8	~8	~8	~8	
Cobalt	~5	~10		~5	~20
Nickel	~40	~30		~20	
Manganese	~5	~15		~80	~20
Iron			~40		~25
Phosphorus			~20		~10

Plug-in hybrid EV (leveraging lead-acid battery)

Lead	~12

Value chain contribution to global demand of minerals and metals (2035)



● High (>50%) ● Moderate (10-50%) ● Low (1-10%) ● Negligible (<1%)

Note: Based on average EV battery size in 2024 of 60 kilowatt-hour (kWh); percentage value refers only to the mass of metals and minerals and not the total vehicle mass.
Sources: S&P Global, ICCT,[4] IEA[5] and Kearney analysis

1.2 The hidden footprint of digitalization

Consultations revealed that awareness of mineral reliance among data centre actors remains low despite accelerating demand. Rapid expansion of hyperscale and AI-optimized facilities is creating a new layer of mineral demand beyond traditional manufacturing. By 2035, data centres are projected to account for about 6% of global gallium use and some 2.4% of germanium demand. While relatively small in volume, these minerals are critical to enable efficient, high-performance computing.

Breaking down the data centre into its key subsystems highlights how different functions – from computing to cooling – depend on distinct sets of materials and drive exposure to a wide range of refined metals.

Servers and chips

Although moderate in overall mass, the compute layer concentrates high-value, high-purity materials – silicon, gallium, germanium, gold, silver and tin – that underpin performance and reliability.

Networking and storage

Networking and facility-level storage hardware represents limited mass but depends on a complex mix of refined metals (such as copper and aluminium) and specialty materials to deliver conductivity, signal precision and thermal stability.

Cooling systems

Cooling and heat-rejection infrastructure accounts for the largest share of total metal mass, dominated by aluminium, copper and steel.

Electrical systems

Power-distribution – switchgear, transformer cabling – is among the most copper- and iron-intensive part of data centre construction and a major cost and schedule driver.

Backup power

Backup systems integrate generators, batteries, converters and switchgear that collectively anchor power reliability and build system redundancy.

Trend: Rising compute intensity, power demand and thermal loads are reshaping materials use in data centres – increasing reliance on copper and aluminium for power and cooling systems, expanding exposure to gallium, silicon carbide and other specialized semiconductors, and adding new dependencies on lithium-ion technologies for backup power.[6]

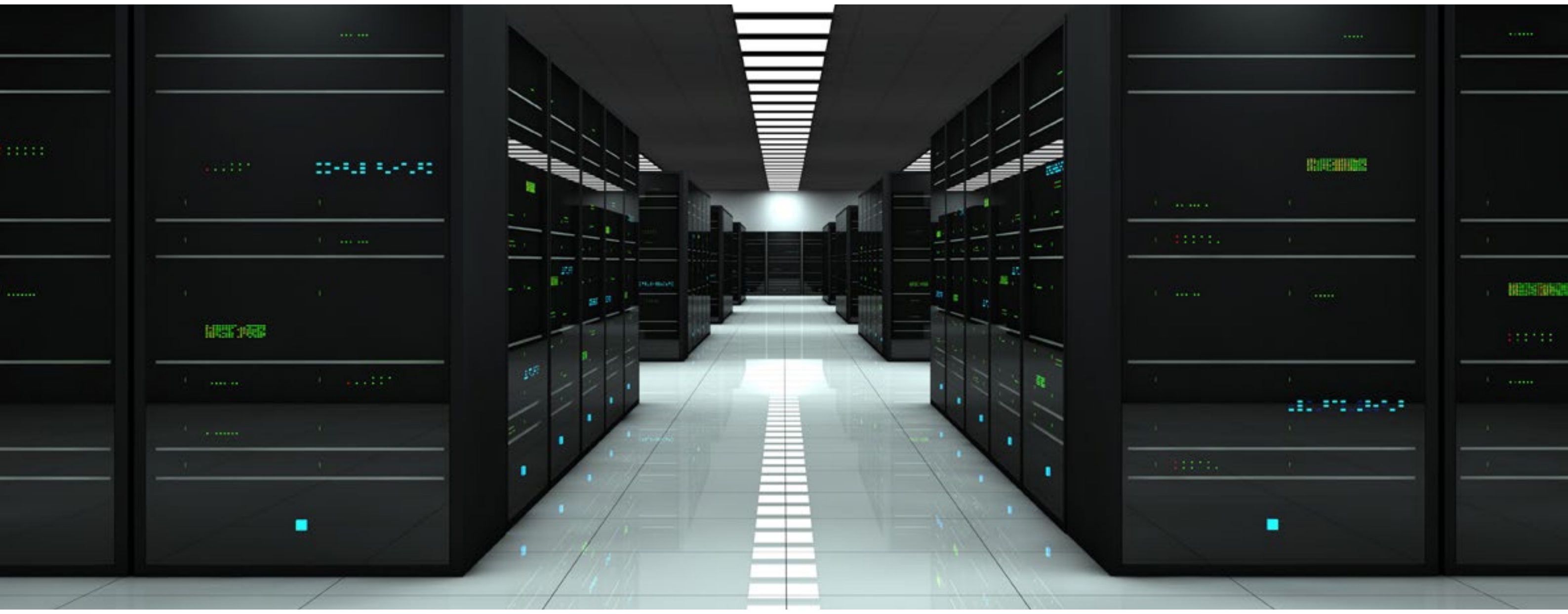
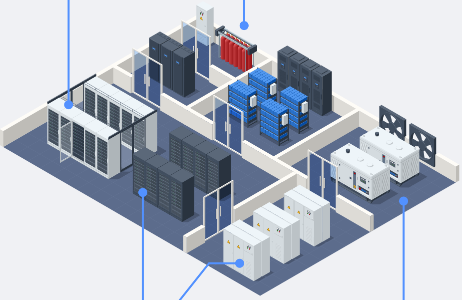


FIGURE 4 Data centre component breakdown by mineral (kgs per MW)

Total minerals and metals mass per MW: ~60-75 metric tons



Networking and storage

~1-3% of minerals and metals used in data centres

Network hardware and facility-level storage

Aluminium	~260
Cobalt	~1
Copper	~280
Germanium	~0.1
Gallium	~0.3
Gold	<0.1
Graphite	~1
Iron	~660
Nickel	~15
REEs	~1
Silicon	~20
Silver	~0.5
Tin	~10

Cooling systems

~35-45% of minerals and metals used in data centres

CRAH/C,[2] CDUs,[3] chillers, cooling tower

Aluminium	~6,700
Copper	~3,600
Gold	<0.1
Graphite	~15
Iron	~18,000
Lead	~10
Nickel	~130
REEs	<0.1
Silicon	~15
Silver	<0.1
Tin	~0.1

Servers and chips (compute

~12-16% of minerals and metals used in data centres

CPUs, GPUs, memory, local storage

Aluminium	~2,700
Cobalt	~2
Copper	~2,000
Germanium	~0.3
Gallium	~2
Gold	~1
Graphite	~5
Iron	~5,100
Lead	~15
Nickel	~35
REEs	~2
Silicon	~160
Silver	~5
Tin	~120

Electrical systems

~15-20% of minerals and metals used in data centres

Switchgear, PDUs,[1] cabling

Aluminium	~460
Copper	~3,500
Germanium	~0.1
Gold	~0.2
Iron	~9,900
Nickel	~70
REEs	~0.4
Silcon	~5
Silver	~1
Tin	~5

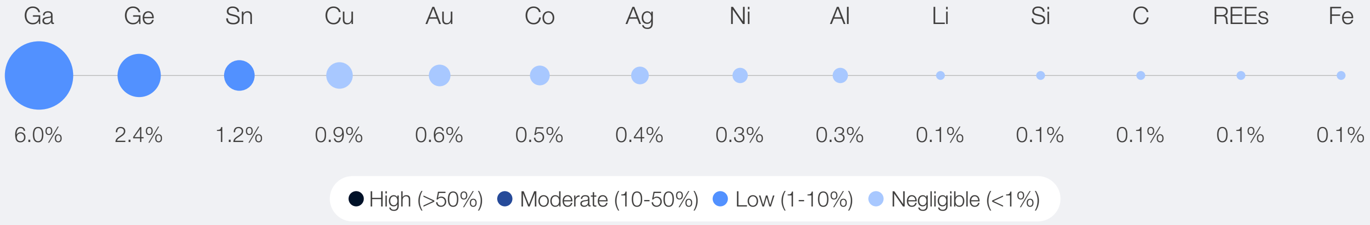
Backup power

~20-30% of minerals and metals used in data centres

Generators, UPS (li-ion/lead-acid)

Aluminium	~1,200
Cobalt	~40
Copper	~2,200
Gold	<0.1
Graphite	~290
Iron	~14,000
Lead	~240
Lithium	~30
Nickel	~220
REEs	~0.2
Silicon	~10
Silver	~0.5
Tin	~2

Value chain contribution to global demand of minerals and metals (2035)



Notes: Based on a 2024 split of conventional (CPU or central processing unit-driven) data centres at 76% capacity vs. accelerated (GPU or graphics processing unit-driven) data centres at 24% capacity. [1] Power distribution unit. [2] Computer room air handler/conditioner. [3] Cooling distribution unit.

Source: Bank of America Securities, IEA and Kearney analysis

1.3 Copper and steel for electrification

Awareness of the grid's mineral intensity – particularly its reliance on copper and grain-oriented electrical steel (GOES) – is rising, as reflected by recent studies and by the consultations with industry players. ET&D systems rank among the most metal-intensive infrastructure segments, comparable to transport and construction in their reliance on bulk metals.[7]

By 2035, grids are expected to account for about 29% of global vanadium demand, 18% of copper and 7% of lithium, underscoring how expansion will increasingly depend on secure, diversified mineral supply.

Decomposing the grid into its main physical components shows where material demand concentrates and how it defines project timelines and resilience.

Towers and poles

Structures account for the largest share of total ET&D metal mass, driven by extensive use of steel, aluminium and protective zinc coatings. Steel fabrication determines both cost and lead time, while aluminium reduces weight for long-span transmission lines.

Substations and transformers

Substations and transformers combine copper windings, GOES cores, and structural iron and aluminium frames.

Electricity cables

Copper and aluminium are the principal conductors in transmission and distribution cables, supported by steel for sheathing and structural reinforcement. Material selection depends on voltage, cost and weight considerations.

Battery energy storage systems (BESS)

BESS are emerging as a new grid asset class to reinforce the reliability of fluctuating renewable power generation. Material needs vary by chemistry: lithium-ion systems rely on lithium, nickel and graphite; sodium-ion systems use iron and aluminium; and vanadium redox-flow systems draw on vanadium and phosphorus.

Trend: Grid expansion and electrification are intensifying demand for copper, aluminium and electrical steel, and tightening supply chains for cables and transformers, while emerging battery storage technologies add new dependencies on lithium, iron, phosphate and vanadium.[8]

FIGURE 5 | ET&D infrastructure component breakdown by mineral (kg per grid km)

Total minerals and metals mass per km ET&D grid length (2035): ~9,000-12,000 kg

Towers and poles

~40-50% of minerals and metals used in ET&D

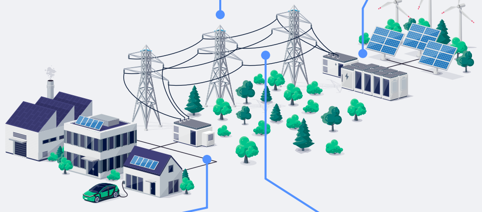
	Minerals	Poles	Towers
●	Aluminium	~510	~450
●	Zinc	~102	~50
●	Iron	~1,200	~2,700

Substations and transformers

~25-27% of minerals and metals used in ET&D

Transformers, switchgear and circuit breakers, busbars and connectors, yard structures

●	Aluminium	~10
●	Electrical steel	~1,300
●	Copper	~750
●	Iron	~890
●	Zinc	<1



Battery energy storage

~5-10% of minerals and metals used in ET&D

	Minerals	Redox flow	Sodium ion	LFP
●	Vanadium	~700		
●	Graphite	~20		~200
●	Iron	~1,500	~200	~150
●	Aluminium	~600	~60	~150
●	Copper	~80		~100
●	Phosphorus		~300	~70
●	Lithium			~20
●	Silicon			~100

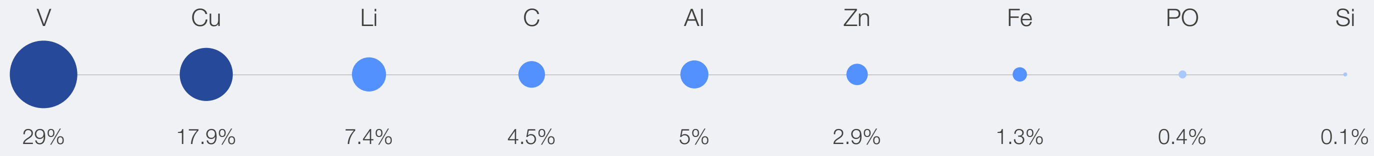
Electricity cables

~20-30% of minerals and metals used in ET&D

Transmission/distribution lines (overhead and underground)

	Minerals	Transmission	Distribution
●	Aluminium	~1,200	~700-~1,700
●	Copper		~500-~2,500
●	Iron	~500	~400

Value chain contribution to global demand of minerals and metals (2035)



● High (>50%) ● Moderate (10-50%) ● Low (1-10%) ● Negligible (<1%)

Notes: Figures are normalized to kg/km: lines from typical conductor sizes and spans; substations/transformers apportioned by asset density per km; civil works excluded

Sources: Bloomberg, IEA, OEMs and Kearney analysis

2

Supply chains disjointed by tiers, territories and timelines

Multi-tiered and geographically dispersed value chains grow differently, creating complex interdependencies and testing coordination and system resilience.

EVs dominate battery-metal consumption, the grid takes up the bulk of metals like copper and aluminium, and data centres need high-purity inputs for chips and power electronics. Together, they set the tone for global minerals trade and processing priorities.

The three value chains share a common structure that begins with mineral extraction and extends through multiple processing and manufacturing stages to final assembly and operation. Each tier involves different stakeholders, from miners and chemical processors to component makers, original equipment manufacturers (OEMs), engineering, procurement and construction companies (EPCs) and utilities, often operating across distant geographies, which adds to the overall complexity and interdependence.

This complexity, amplified by the distance between tiers, creates both awareness and visibility gaps – making it difficult for stakeholders to anticipate where capacity will be needed or how timelines align, underscoring the importance of early coordination and planning for resilience.

Consultations across upstream and downstream participants confirmed that they don't communicate frequently. Many of the downstream players consulted said they do not yet track minerals risks as continuity risks and almost all pointed to the "distance" between tiers as a barrier to coordination.

Across value chains, capacity additions follow similar patterns but on very different timelines.

- **Mining projects** in some jurisdictions require **10-20 years** from discovery to production, reflecting permitting, infrastructure and financing hurdles.[9]
- **Refining facilities** take **three to eight years**[10] to develop, depending on permitting requirements, construction complexity and customer qualification.
- **Manufacturing and end-product facilities** can be commissioned within **one to five years**, reflecting shorter construction cycles and fewer regulatory constraints.

These disparities matter most when new capacity is urgently needed, as downstream segments can scale far faster than upstream supply can adjust – impacting the underlying demand drivers for materials. These indicative lead times are common across EVs, data centres and ET&D, but each value chain exhibits specific bottlenecks and timing gaps that will be discussed in the following subsections.

The vulnerability doesn't arise from linear queues, it arises when a specific enabler – permits, technology and supplier qualification, component capacity or interconnections – lags behind demand.

There is also a strategic planning horizon mismatch – miners plan for 10- to 15-year cycles while downstream players typically look two to five years ahead. Misaligned development timelines create a structural challenge for supply resilience. When upstream investment slows or permitting slips – or when a mine sanctioned on yesterday's outlook comes online after technology, specifications or siting have shifted – projects face higher costs, re-sourcing/retooling or idle capacity that cascades downstream. Such timing mismatches amplify costs and delays across value chains. Anticipating these timing gaps and planning capacity early is essential to keep supply and demand aligned as electrification and digitalization accelerate.

The following sections examine how these dynamics manifest across EV, data centres and grid value chains – each revealing distinct pressures, geographic realities and opportunities for resilience.

2.1 Anatomy of the electric mobility supply chain

A tightly integrated yet geographically concentrated system defines EV manufacturing. Battery, motor and electronics production have scaled rapidly, but dependence on a few refining and assembly hubs leaves the chain exposed to policy, trade and logistics risks.

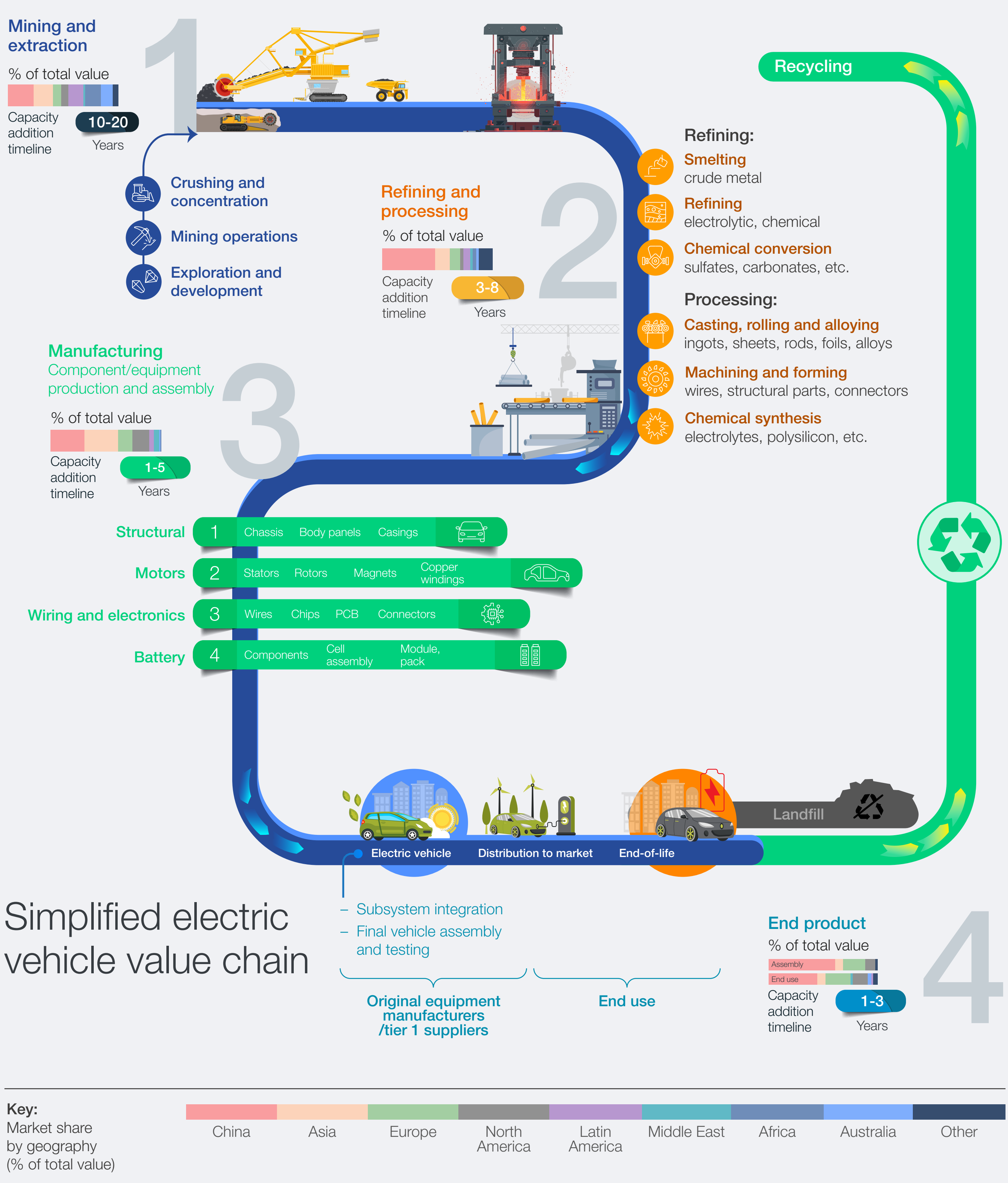
- **Supply tiers that multiply exposure:** Each stage of the EV value chain involves more than 10 distinct tiers of suppliers, from miners and chemical processors to cathode, anode and component manufacturers, creating interdependent lead times across the system.

- **Fast ramp-up, slow foundations:** New EV manufacturing assets – battery gigafactories,[11] motors, power electronics and structural components – typically ramp up within one to three years,[12] with final assembly over two years,[13] far faster than mining or refining capacity can adjust.

- **Circularity still waiting to kick in:** End-of-life management remains nascent. Recoverable battery volumes are expected only after 2030, as vehicles sold in the early 2020s reach retirement age.[14]

- **Geography as both advantage and exposure:** The industry's production footprint is highly concentrated. Battery-cell manufacturing and the underlying cathode/anode technology and R&D are used as a proxy for manufacturing locations. China holds the dominant market shares: approximately 50% of global minerals refining, 70% of battery manufacture and 70% of EV assembly.[15] This structure has enabled rapid cost declines through integrated supply chains and learning-curve effects, but it also heightens exposure to policy, trade and logistics disruptions that can cascade through the value chain.[16]

FIGURE 6 | **Simplified EV value chain and region of production for each value chain segment**



Sources: USGS,[17] IEA and Kearney analysis

2.2 Structure of the digital infrastructure supply chain

An increasingly material-intensive digital backbone faces limited visibility across a long, complex chain. Rapid growth in hyperscale and AI-optimized facilities has multiplied dependencies on high-purity metals and semiconductors, but awareness of this reliance remains low among many operators.

- **Interconnected systems, invisible dependencies:** The data centre value chain links upstream materials and component manufacturing to complex facility integration. Multiple subsystems – computing, power, cooling and networking – are assembled in parallel, creating more than 14 interdependent supply tiers.

- **Timelines that can't keep up with compute demand:** Greenfield semiconductor fabrication plants typically require three to five years from investment to output,[18] while servers,[19] power and cooling[20] equipment facilities are completed in one to three. New-build data centres take nine to 36 months, often in phases depending on scale.

- **Circularity – still more potential than practice:** End-of-life and secondary supply from decommissioned facilities yield recoverable copper, aluminium, steel and REEs. Circular practices for semiconductors and unlimited power supply (UPS) batteries remain limited but are expected to scale later in the decade.

- **Concentration where chips are made – and consequent risks:** Semiconductor manufacturing – central to CPUs, GPUs and memory chips – remains concentrated in East Asia (China has a 24% market share, Taiwan 18%, South Korea 18% and Japan 15%).[21] Construction is distributed across North America and Europe, and emerging in Asia. This split supports cost efficiency but increases exposure to semiconductor bottlenecks, trade restrictions and logistics risks.

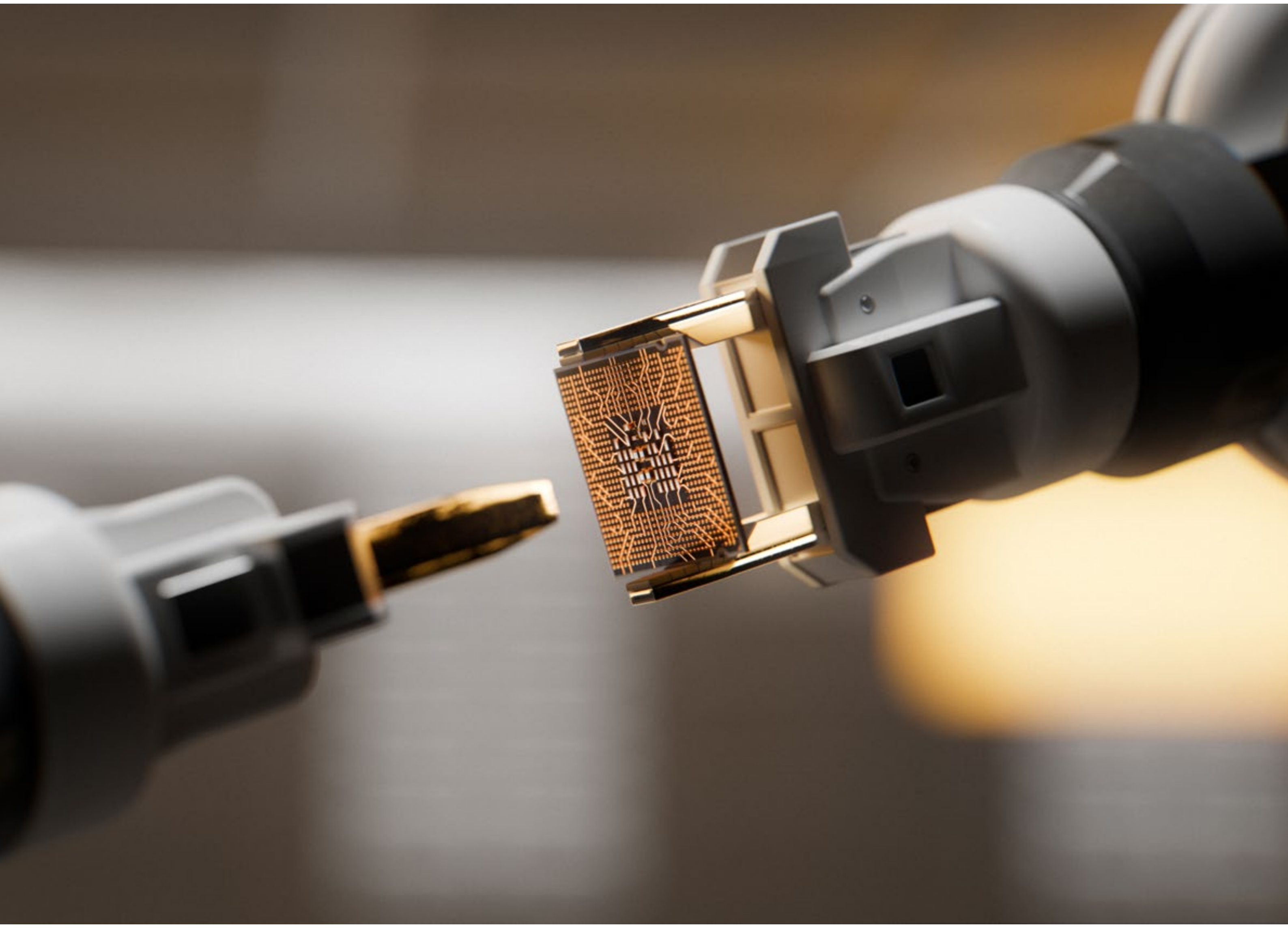
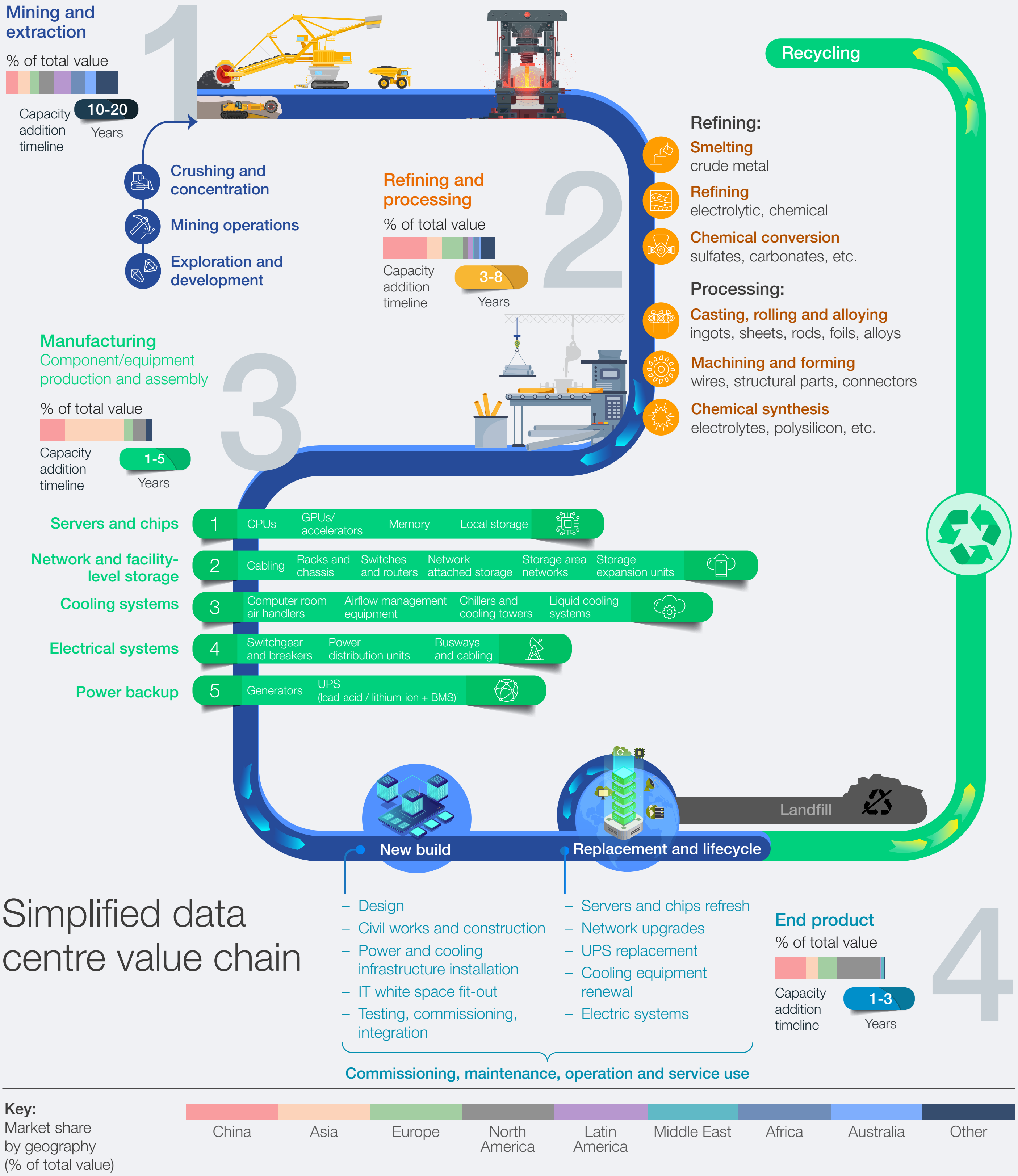


FIGURE 7 | **Simplified data centre value chain and region of production for each value chain segment**



Simplified data centre value chain

1 Mining and extraction

% of total value

Capacity addition timeline: 10-20 Years

- Crushing and concentration
- Mining operations
- Exploration and development

2 Refining and processing

% of total value

Capacity addition timeline: 3-8 Years

Refining:

- **Smelting** crude metal
- **Refining** electrolytic, chemical
- **Chemical conversion** sulfates, carbonates, etc.

Processing:

- **Casting, rolling and alloying** ingots, sheets, rods, foils, alloys
- **Machining and forming** wires, structural parts, connectors
- **Chemical synthesis** electrolytes, polysilicon, etc.

3 Manufacturing

Component/equipment production and assembly

% of total value

Capacity addition timeline: 1-5 Years

Servers and chips	1	CPUs, GPUs/accelerators, Memory, Local storage
Network and facility-level storage	2	Cabling, Racks and chassis, Switches and routers, Network attached storage, Storage area networks, Storage expansion units
Cooling systems	3	Computer room air handlers, Airflow management equipment, Chillers and cooling towers, Liquid cooling systems
Electrical systems	4	Switchgear and breakers, Power distribution units, Busways and cabling
Power backup	5	Generators, UPS (lead-acid / lithium-ion + BMS)[1]

New build

- Design
- Civil works and construction
- Power and cooling infrastructure installation
- IT white space fit-out
- Testing, commissioning, integration

Replacement and lifecycle

- Servers and chips refresh
- Network upgrades
- UPS replacement
- Cooling equipment renewal
- Electric systems

Commissioning, maintenance, operation and service use

4 End product

% of total value

Capacity addition timeline: 1-3 Years

Recycling

Landfill

Key: Market share by geography (% of total value)

China | Asia | Europe | North America | Latin America | Middle East | Africa | Australia | Other

Note: [1] Battery management system

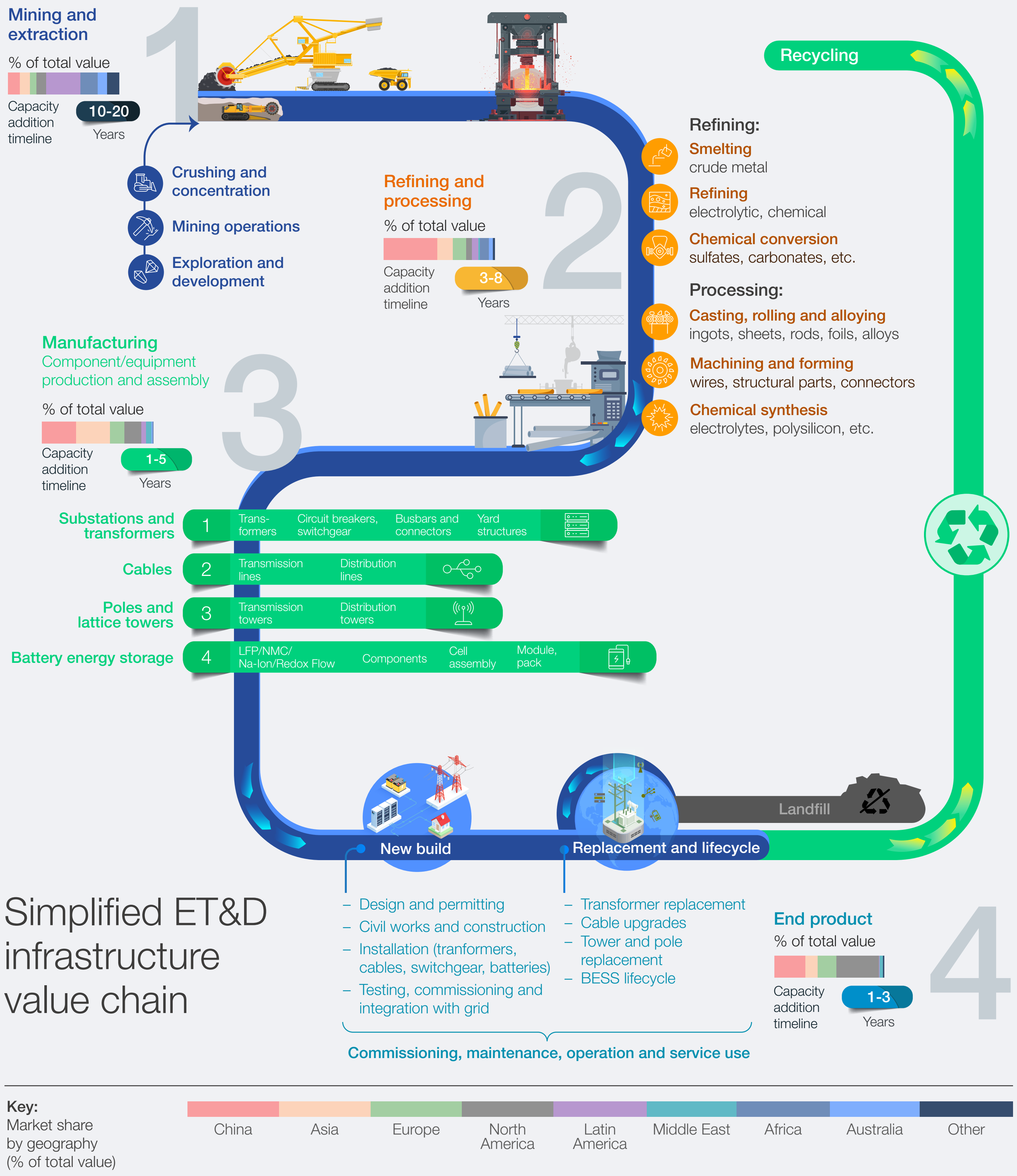
Sources: USGS, IEA, JP Morgan Asset Management, Gartner and Kearney analysis

2.3 Map of the grid supply chain

Grid infrastructure combines long build cycles with uneven regional capacity. Expansion depends on heavy industrial inputs and sequential processes that define both timing and resilience.

- **Complex supply tiers that dictate the pace of progress:** Multiple industrial tiers (more than 12) – conductors, transformers, switchgear and structural components – interact through long build-out sequences that set the pace for grid expansion.
- **Lead times measured in years, not quarters:** New transformer factories take two to four years to commission,[22] high-voltage direct current (HVDC) facilities three to five,[23] and tower/pole fabrication plants 12 to 24 months.[24] Transmission-line and substation integration extends nine to 36 months, depending on terrain and coordination.
- **Circularity limited by asset longevity:** Unlike vehicles or electronics, grid assets have decades-long lifespans and slow turnover. Near-term secondary flows are therefore modest, though recycling of decommissioned copper and steel components is well-established.
- **Geography shapes supply – and delays:** Manufacturing capacity is regionally dispersed but uneven. China and East Asia account for roughly 31% of transformer output, supported by large domestic steel and aluminium industries. Europe and North America retain advanced design and testing capabilities but face shortages of large-power transformers and HVDC equipment, extending delivery times and delaying grid modernization.

FIGURE 8 **Simplified ET&D infrastructure value chain and region of production for each value chain segment**



Simplified ET&D infrastructure value chain

1 Mining and extraction
% of total value
Capacity addition timeline: 10-20 Years

- Crushing and concentration
- Mining operations
- Exploration and development

2 Refining and processing
% of total value
Capacity addition timeline: 3-8 Years

Refining:
- **Smelting** crude metal
- **Refining** electrolytic, chemical
- **Chemical conversion** sulfates, carbonates, etc.

Processing:
- **Casting, rolling and alloying** ingots, sheets, rods, foils, alloys
- **Machining and forming** wires, structural parts, connectors
- **Chemical synthesis** electrolytes, polysilicon, etc.

3 Manufacturing
Component/equipment production and assembly
% of total value
Capacity addition timeline: 1-5 Years

Substations and transformers	1	Trans-formers	Circuit breakers, switchgear	Busbars and connectors	Yard structures
Cables	2	Transmission lines	Distribution lines		
Poles and lattice towers	3	Transmission towers	Distribution towers		
Battery energy storage	4	LFP/NMC/ Na-Ion/Redox Flow	Components	Cell assembly	Module, pack

Recycling

Landfill

New build
- Design and permitting
- Civil works and construction
- Installation (tranformers, cables, switchgear, batteries)
- Testing, commissioning and integration with grid

Replacement and lifecycle
- Transformer replacement
- Cable upgrades
- Tower and pole replacement
- BESS lifecycle

Commissioning, maintenance, operation and service use

4 End product
% of total value
Capacity addition timeline: 1-3 Years

Key:
Market share by geography (% of total value)
China, Asia, Europe, North America, Latin America, Middle East, Africa, Australia, Other

Sources: USGS, Transformers Magazine,[25] IEA and Kearney analysis

3 Shared risks, divided attention

Minerals-intensive value chains face physical bottlenecks and systemic gaps that can quickly delay equipment deliveries and increase project costs for downstream players.

Mineral supply for EVs, data centres and ET&D faces two kinds of exposure: physical bottlenecks and system frictions. Concentrated processing, long build times and site constraints limit how fast supply can grow, while weak cross-tier visibility, shifting demand and fragmented standards slow investment and qualification. Because mining, refining and equipment manufacturing operate on different timelines and face distinct vulnerabilities, risk management remains fragmented, turning small shocks into downstream delays and higher costs.

Additionally, vertical integration rarely extends beyond one to three tiers, leaving miners, refiners, component makers and end-product owners weakly connected at the system level. These findings build on the Forum's Securing Minerals for the Energy Transition work,[26] which has identified supply-demand gaps and the societal, environmental and governance risks that continue to shape resilience today.

Despite differing perspectives shared during consultations, four systemic themes have emerged:

- **Fragmented dialogue and visibility gaps:** Distance between upstream and downstream actors creates information gaps and an uneven understanding of one another's risks; dialogue is episodic and bilateral rather than system-wide.

- **Demand uncertainty:** Unclear and constantly changing demand projections across the value chain, driven partly by policy changes and rapidly evolving technologies, hinder investments and planning.

- **Differing risk agendas:** Each tier in the value chain optimizes for its own risks and targets, creating misaligned incentives across the value chain.

- **Low salience and actionability gap:** Mineral risks often seem marginal and sit below nearer-term issues (energy costs, emissions, tier-1 performance); even when flagged, downstream players lack clear, practical levers to act, leaving issues unresolved.

EV OEMs are further along in managing upstream risk than data centres and many ET&D players. The semiconductor shortage halted vehicle production and exposed the limits of single-tier visibility. In response, leading EV manufacturers elevated mineral risk to the executive agenda to avoid repetition. By contrast, mineral governance is less mature in data centres and grids, though some utilities already maintain strong supplier visibility.

3.1 Early warning signs in supply

This section focuses on the minerals and metals that drive the bills of materials for EV, data centre and ET&D value chains, examining capacity signals, supply-demand balances and sources of supply

Emerging supply volatility

Overall supply-demand balances in 2024 were stable, with small gaps in select materials, such as manganese and aluminium, reflecting acute market dynamics – temporary shutdowns, rapid price swings, logistical constraints – rather than structural shortfalls. However, supply volatility is already visible.

In Yunnan, China, droughts repeatedly cut hydropower, curbing aluminium output.[27] Shutdowns like at Bald Hill in Australia removed lithium supply and exposed market fragility.[28] Smelter closures and cutbacks reflect squeezed economics from low – and even negative – copper treatment and refining charges (TC/RCs), with governments and industry warning current fee levels are unsustainable.[29]

Growing regionalization and policy actions are re-routing flows and reinforcing concentration: China introduced export controls on gallium and germanium in 2023[30] and later restricted rare-earth technologies and material exports;[31] Indonesia's nickel-ore export ban increased and concentrated nickel-processing capacity within the country;[32] and the Democratic Republic of the Congo (DRC) imposed cobalt export restrictions,[33] further tightening global supply chains. Even without shocks, output from the current asset base erodes as reserves deplete and ore grades decline.[34] In copper, for example, maintaining flat supply requires ongoing investment – new and sustaining projects must first replace lost volumes before adding net new capacity.

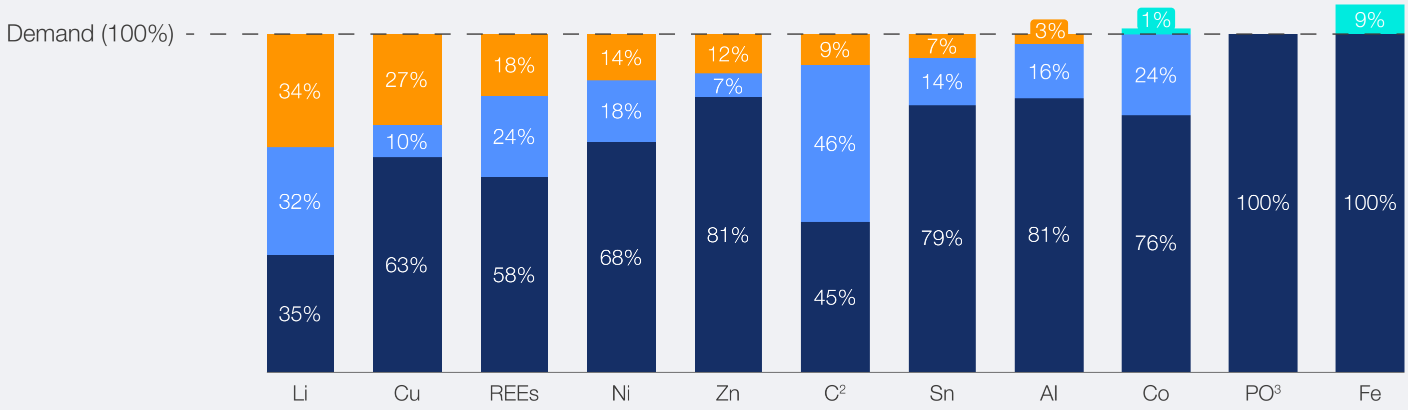
At the same time, new Western projects are advancing. Keliber's lithium hydroxide project in Finland was designated a "Strategic Project" under the European Union's Critical Raw Materials Act (CRMA), a status intended to accelerate permitting and enable access to finance.[35] Thacker Pass secured a $2.26 billion US Department of Energy loan,[36] and the US is channelling cross-border support to allied Canadian projects under the Canada-US Joint Action Plan on Critical Minerals Collaboration to strengthen global supply-chain resilience. The next decade remains a window to prepare before steeper demand tests capacity.

Looking to 2035, forecast tightness stems not only from demand growth but from how much of 2035 supply still needs to be developed. Figure 9 projects that **for several minerals, today's operating base covers only half (or less) of expected 2035 demand, with the balance dependent on projects that must still be permitted, financed or even identified**. For example, today's supply of lithium and graphite covers approximately 35-45% of forecasted 2035 demand; even if announced projects deliver, material shortfalls are expected to persist – implying a near-doubling of output needed within a decade.

Recycling helps but cannot close these gaps alone. Its contributions are meaningful for copper and aluminium – the International Energy Agency (IEA) estimates an average recycled-input share of about 35% for aluminium and approximately 17% for copper (excluding direct-use scrap) over the last decade.[37] However, recycling of lithium and rare earths remains nascent due to low end-of-life volumes and insufficient collection and mechanical-separation capacity.

FIGURE 9

Projected global supply-demand balance for select minerals (2035e)[1]



	Li	Cu	REEs	Ni	Zn	C[2]	Sn	Al	Co	PO[3]	Fe
EVs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Data centres	✓	✓	✓	✓		✓	✓	✓	✓		✓
Electricity infrastructure	✓	✓		✓	✓	✓		✓	✓	✓	✓

● Existing 2024 supply ● Supply additions by 2035 ● Forecast deficit ● Forecast surplus

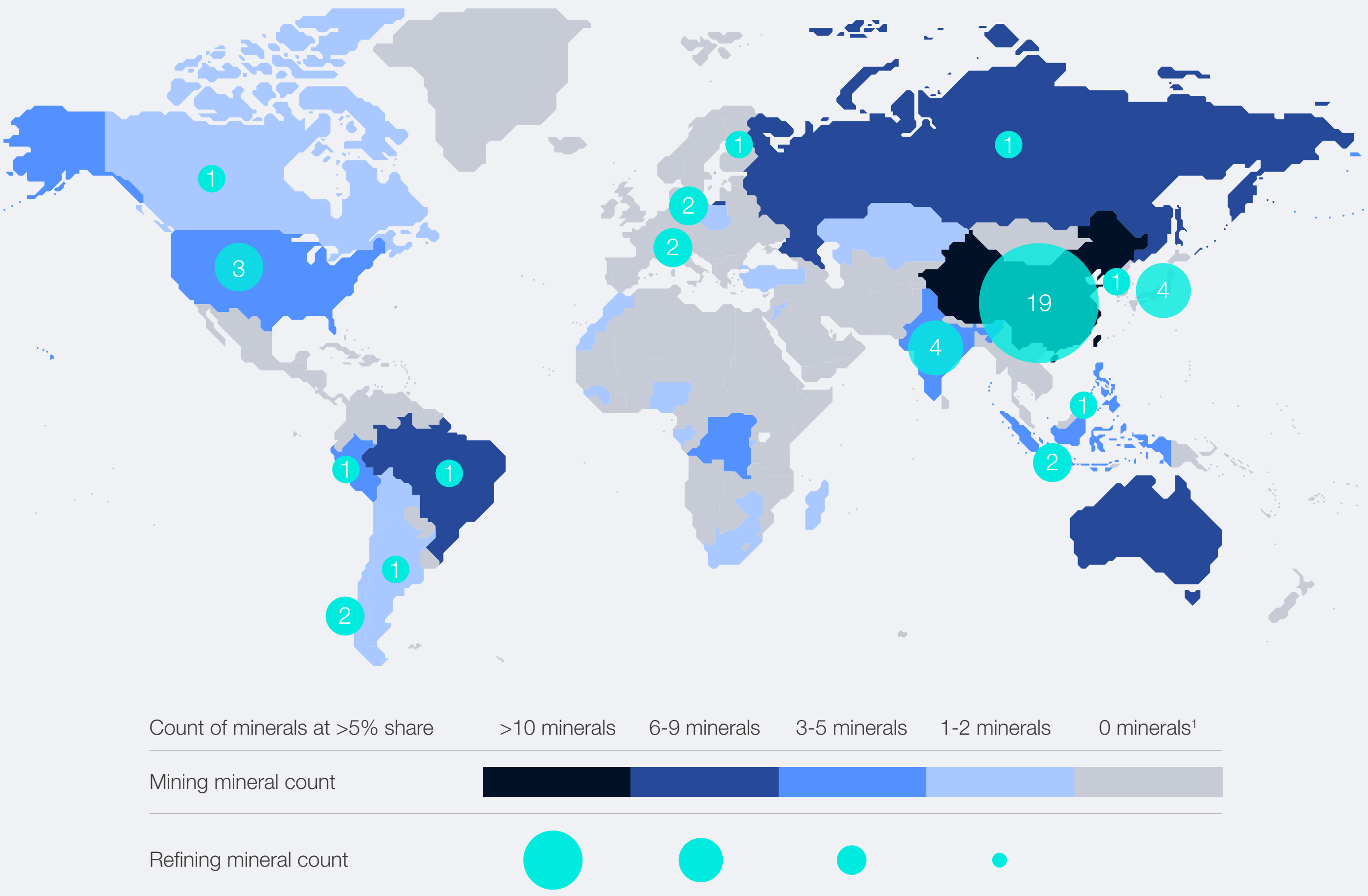
Notes: Balances are indicative and synthesized from multiple sources based on available information; figures may vary by source and assumptions (e.g. demand trajectories, project start-up/ramp, recycling rates). [1] Percentage shortfall/surplus = (forecast refined supply – forecast refined end-demand) ÷ forecast demand (2035e). [2] C: Graphite [3] PO: Phosphates

Sources: IEA, Shanghai Metals Market, CRU (Commodities Research Unit), Association for Iron & Steel Technology, International Lead and Zinc Study Group, USGS, Silver Institute, Research and Markets, International Tin Association, International Aluminium Institute, S&P Global, Wood Mackenzie and Kearney analysis

Concentrated sources of supply

Across EVs, data centres and ET&D, mining is relatively more dispersed, but refining and processing are highly concentrated. The IEA estimates that the top three refining countries' average market share rose from approximately 82% (2020) to 86% (2024),[38] a level of concentration rare in other industrial inputs.

FIGURE 10 **Countries with ≥5% share of mined and refined production of select minerals (2024)**



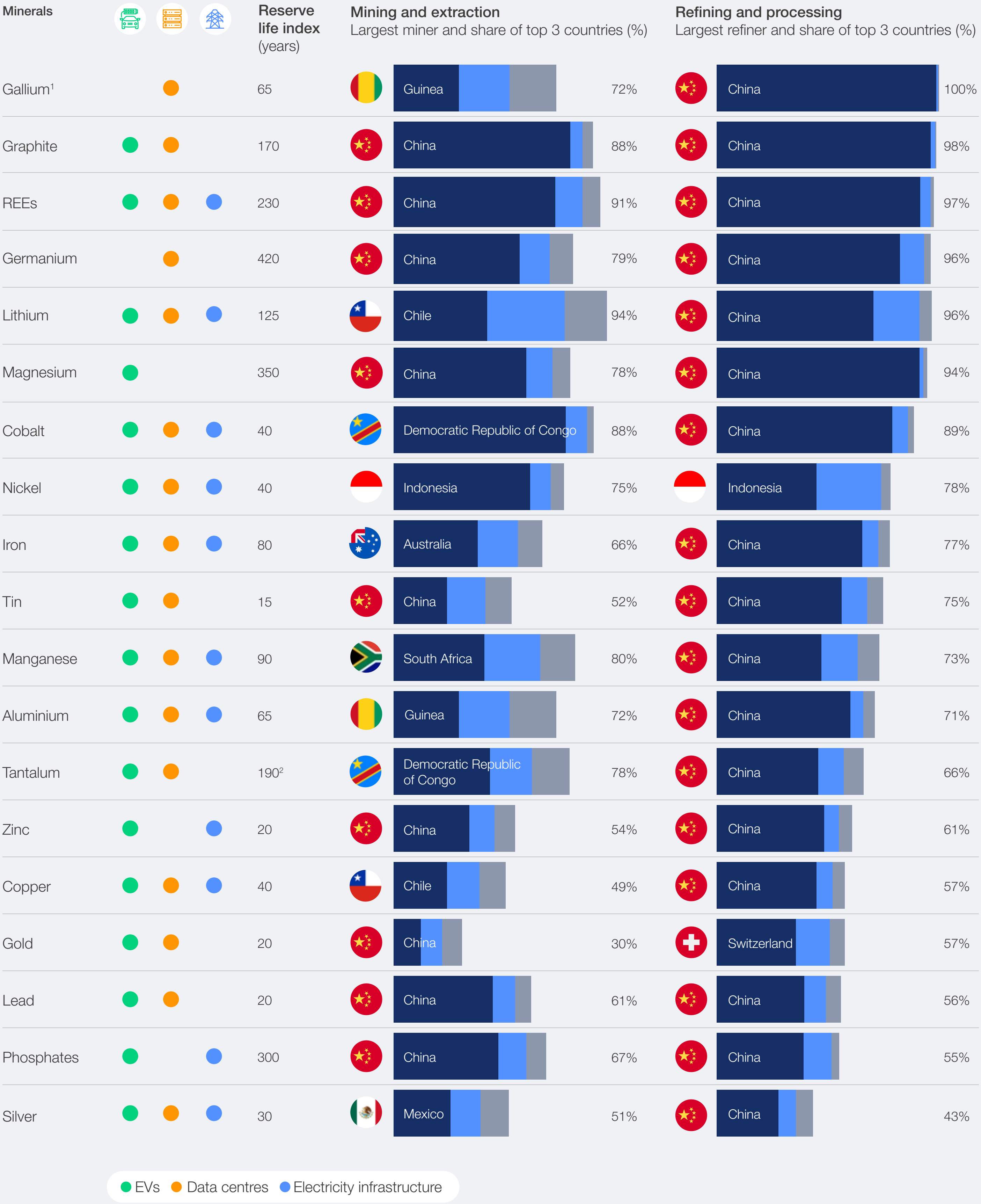
Notes: [1] Includes countries that are involved in mining and/or refining but do not constitute ≥5% market share for the tracked minerals.

Sources: IEA, S&P, USGS and Kearney analysis

- **Mining:** Of the 19[39] tracked minerals, China has ≥5% mined share in 15, Australia in seven and Brazil and Russia each in six – still concentrated for several minerals but more geographically spread than refining.

- **Refining:** China holds ≥5% of refined output for all 19 tracked minerals and exceeds 75% for several (gallium, graphite, REEs, magnesium, germanium and cobalt). Exceptions underscore the rule: Nickel processing is now dominated by Indonesia (often via Chinese-owned assets) and gold refining is more distributed, with Switzerland a major hub. Other smaller hubs include India with market shares ≥5% in four bulk metals (aluminium, iron, zinc and lead) and Japan with four (tantalum, copper, gold and silver).

FIGURE 11 **Reserve life index and mining and refining share of top three countries for select minerals (2024)**



Minerals				Reserve life index (years)	Mining and extraction Largest miner and share of top 3 countries (%)		Refining and processing Largest refiner and share of top 3 countries (%)	
Gallium[1]		●		65	Guinea	72%	China	100%
Graphite	●	●		170	China	88%	China	98%
REEs	●	●	●	230	China	91%	China	97%
Germanium		●		420	China	79%	China	96%
Lithium	●	●	●	125	Chile	94%	China	96%
Magnesium	●			350	China	78%	China	94%
Cobalt	●	●	●	40	Democratic Republic of Congo	88%	China	89%
Nickel	●	●	●	40	Indonesia	75%	Indonesia	78%
Iron	●	●	●	80	Australia	66%	China	77%
Tin	●	●		15	China	52%	China	75%
Manganese	●	●	●	90	South Africa	80%	China	73%
Aluminium	●	●	●	65	Guinea	72%	China	71%
Tantalum	●	●		190[2]	Democratic Republic of Congo	78%	China	66%
Zinc	●		●	20	China	54%	China	61%
Copper	●	●	●	40	Chile	49%	China	57%
Gold	●	●		20	China	30%	Switzerland	57%
Lead	●	●		20	China	61%	China	56%
Phosphates	●		●	300	China	67%	China	55%
Silver	●	●	●	30	Mexico	51%	China	43%

● EVs ● Data centres ● Electricity infrastructure

Notes: [1] Gallium derives mainly from bauxite (aluminium) ore and not as standalone deposits; mining concentration reflects bauxite production
[2] Tantalum reserve life index shown is a floor estimate, based on global mined output and the reported reserves of Australia, Brazil and China

Sources: IEA, S&P, USGS and Kearney analysis

Short reserve-life combined with high production and refining concentration elevates risk exposure. Bulk system metals such as copper warrant special attention given their centrality across all three value chains.

Additionally, **for several specialty materials – graphite, REEs, germanium, lithium, magnesium, cobalt, nickel, manganese and tantalum – the top three mining and refining countries hold >75% of the market share**. This heightens exposure to single-point disruptions such as operational outages or export controls, which can trigger global price or schedule shocks – even when aggregate supply appears adequate.

Ownership patterns add another layer: cross-border corporate control can diversify financing and expertise, but it can also transmit policy risk across regions, thereby shifting strategic control of assets.

For the minerals tracked in this report, a disruption at the largest producer creates a material risk of unmet global demand and lasting downstream impacts, making market concentration a key challenge to supply chain resilience.

3.2 Upstream shocks, downstream consequences

Because processing is concentrated and qualification of new suppliers, materials or technologies takes time, local shocks upstream quickly become delivery risks downstream. Figure 12 maps the chain of disruption, outlining how issues in mining and refining can translate into component delays and end-product slippage.

One example is GOES, essential for transformer cores, where limited global capacity – further squeezed by the Russia/Ukraine-related trade restrictions – has collided with strong demand and skilled-labour shortages. With GOES scarce, transformer prices have increased 50-80% over the last three years and lead times have stretched to about 18-36 months, forcing order reprioritization.[40] Downstream, utilities and developers have delayed grid connections, pushing back EV-charger rollouts and data centre energization.

Price dynamics matter. Spikes can unlock financing and accelerate projects; beyond a threshold, they trigger substitution and design pivots, increasing uncertainty for suppliers. In such periods, investors may pause or delay final investment decisions (FIDs) until technology choices and demand signals stabilize, prolonging the bottlenecks that higher prices were meant to relieve.

FIGURE 12 **Cascading risk impact from upstream production to downstream delivery**

	Mining and extraction	Refining and processing	Manufacturing	End products
Gallium and germanium export restrictions	– **90%+** gallium and germanium **production concentrated in China** – **Export licence restrictions** limited flows to the US, EU, others (2023); total ban to the US in 2024		**Increasing costs and higher lead times** disrupting sensor, chip, semiconductor and fibre optics supply	**Slower rollout of data centres,** AI hardware and advanced EV electronics
Grain-oriented electrical steel (GOES) bottleneck	Iron ore widely available	**Limited GOES production** capacity, further strained by Russia/Ukraine war	**Lower availability and higher costs of GOES** for transformer cores	**Higher lead times** for transformers delaying grid build-out and maintenance, impacting EV and data centre growth
Copper production expansion delays	**Permitting** challenges, **water constraints** and community **opposition** in Peru/Chile; lack of committed projects to fulfil demand	**Refined copper output bottlenecks,** exacerbated by smelter closures and poor refining margins	**Higher costs, longer lead times** for cable and transformer producers	**Delays in new grid capacity** impacting EV charging networks and data centre power supply

Across very different bottlenecks, the risk pattern is similar: capacity may exist in aggregate but arrives too late or at a higher price than anticipated, so costs rise and schedules slip before supply can be requalified or redirected. **Demand surges in one value chain tighten the same metals and equipment others need; as EV, data centre and grid build-outs draw on overlapping inputs such as copper, electrical steel and semiconductors, short-term trade-offs emerge – reinforcing the need for dialogue and coordinated planning.** With capacity concentrated in a few hubs, policy or operational shocks propagate across the system. Without coordination, procurement becomes zero-sum – with higher prices and longer delays for everyone.

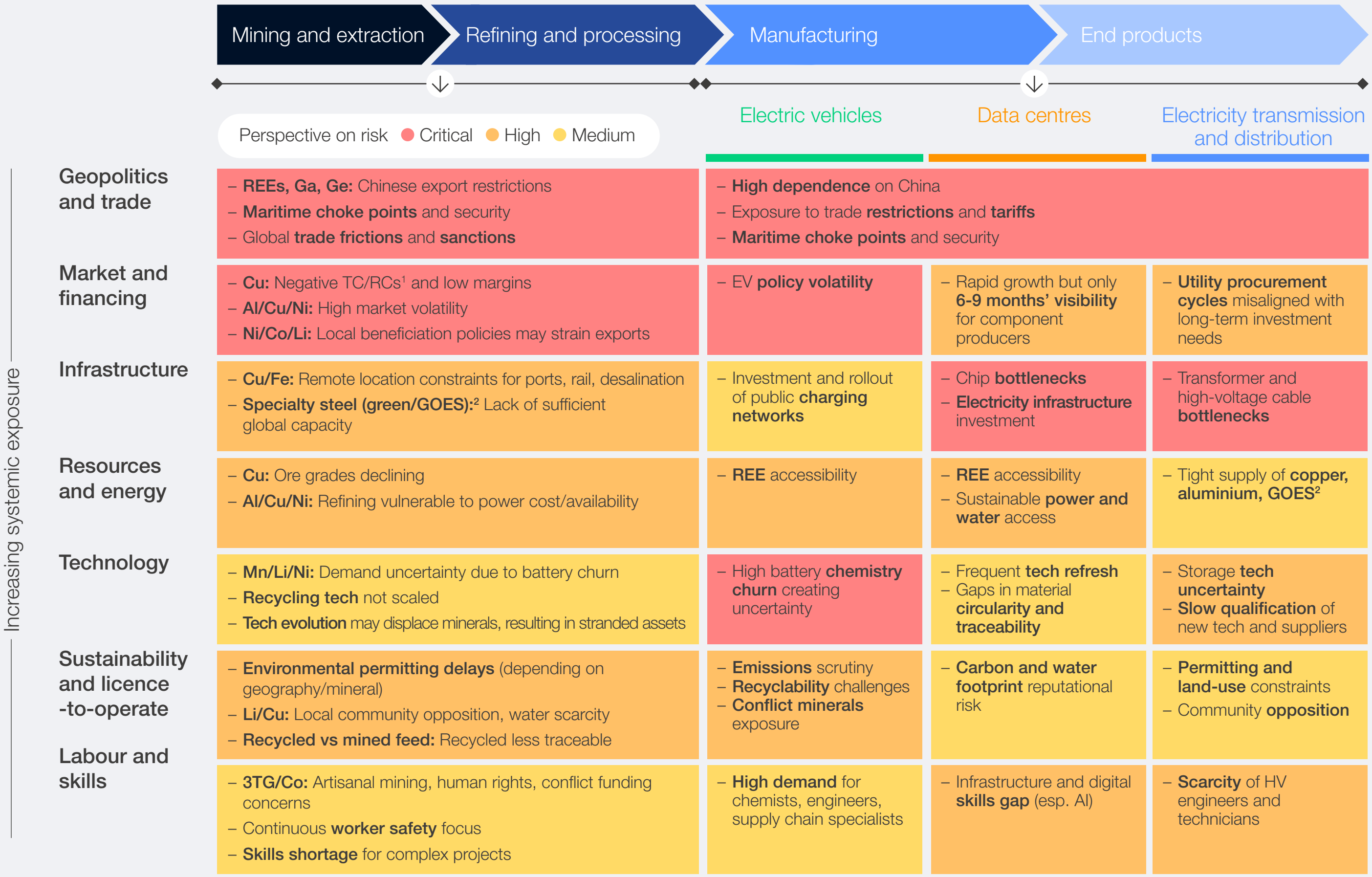
3.3 Competing risk agendas

Risk perspectives differ by tier and shared understanding of each other's exposure is uneven, yet recurring patterns appear across EVs, data centres and ET&D, compounding from mining to end products. During consultations, executives across value chains shared their top risks, which were subsequently translated into seven risk vectors. Figure 13 maps how these risks concentrate across tiers and highlights how priorities differ by value chain step. High supply concentration amplifies each, turning local shocks into global impact.

Across consultations, three risks dominated:

- **Geopolitics and trade:** Proliferating trade rules that regionalize supply and increase lead-time and price uncertainty.
- **Market and financing:** Industrial policy volatility – incentives, local-content rules, licensing – that compress margins and rewire demand signals.
- **Infrastructure:** Not just ports, rail and power to upstream sites, but thin capacity for critical components and downstream grid readiness that gate new capacity and extend queues.

FIGURE 13 **Risk perspectives across the value chain**



Perspective on risk 🔴 Critical 🟠 High 🟡 Medium

		Electric vehicles	Data centres	Electricity transmission and distribution
Geopolitics and trade	🔴 – **REEs, Ga, Ge:** Chinese export restrictions – **Maritime choke points** and security – Global **trade frictions** and **sanctions**	🔴 – **High dependence** on China – Exposure to trade **restrictions** and **tariffs** – **Maritime choke points** and security		
Market and financing	🔴 – **Cu:** Negative TC/RCs[1] and low margins – **Al/Cu/Ni:** High market volatility – **Ni/Co/Li:** Local beneficiation policies may strain exports	🔴 – EV **policy volatility**	🟠 – Rapid growth but only **6-9 months' visibility** for component producers	🟠 – **Utility procurement cycles** misaligned with long-term investment needs
Infrastructure	🟠 – **Cu/Fe:** Remote location constraints for ports, rail, desalination – **Specialty steel (green/GOES):**[2] Lack of sufficient global capacity	🟡 – Investment and rollout of public **charging networks**	🔴 – Chip **bottlenecks** – **Electricity infrastructure** investment	🔴 – Transformer and high-voltage cable **bottlenecks**
Resources and energy	🟠 – **Cu:** Ore grades declining – **Al/Cu/Ni:** Refining vulnerable to power cost/availability	🟠 – **REE** accessibility	🟠 – **REE** accessibility – Sustainable **power and water** access	🟡 – Tight supply of **copper, aluminium, GOES**[2]
Technology	🟡 – **Mn/Li/Ni:** Demand uncertainty due to battery churn – **Recycling tech** not scaled – **Tech evolution** may displace minerals, resulting in stranded assets	🔴 – High battery **chemistry churn** creating uncertainty	🟡 – Frequent **tech refresh** – Gaps in material **circularity and traceability**	🟠 – Storage **tech uncertainty** – **Slow qualification** of new tech and suppliers
Sustainability and licence -to-operate	🟠 – **Environmental permitting delays** (depending on geography/mineral) – **Li/Cu:** Local community opposition, water scarcity – **Recycled vs mined feed:** Recycled less traceable	🟠 – **Emissions** scrutiny – **Recyclability** challenges – **Conflict minerals** exposure	🟡 – **Carbon and water footprint** reputational risk	🟡 – **Permitting and land-use** constraints – Community **opposition**
Labour and skills	🟡 – **3TG/Co:** Artisanal mining, human rights, conflict funding concerns – Continuous **worker safety** focus – **Skills shortage** for complex projects	🟡 – **High demand** for chemists, engineers, supply chain specialists	🟠 – Infrastructure and digital **skills gap** (esp. AI)	🟠 – **Scarcity** of HV engineers and technicians

Note: The heatmap reflects the frequency with which participants cited the particular risk among top risks; this is not a ranked survey.
[1] TC/RCs: Treatment and refining charges. [2] GOES: Grain-oriented electrical steel

Source: Authors

Geopolitics and trade

Mining and refining: Trade and industrial policies are reshaping where value is added and who gets material first. Export controls (e.g. on REEs, gallium and germanium), sanctions and tariffs – from US duties on aluminium and copper to Canada's licence recissions[41] – have introduced new layers of planning uncertainty. Maintaining open and predictable trade remains critical to resilience and affordability.

Component manufacturing and end products: OEMs in EVs and grid equipment reported heavy dependence on Chinese processing and components, leaving them vulnerable to regulatory shifts and logistics shocks. Maritime disruptions, such as the 2023-24 Red Sea[42] re-routing, demonstrated how choke points can ripple through global supply chains. Cross-border grid interconnections also face misaligned national policies and permitting delays.

> “ Trade and industrial policy can change mid-build. Our operational risk therefore becomes planning certainty: whether we will be able to access materials at the time and price we anticipated and whether policy will still support our projected growth.

Market and financing

Mining and refining: Margins are tightening and investment decisions are delayed. Low TC/RCs (treatment charges or refining charges – the fees paid to smelters/refiners by miners for converting ore or concentrates) and policy volatility slow new refining projects while accelerating closures. Subsidy-driven competition, price swings and localization rules create uncertainty over where capacity will emerge – and which assets may be stranded.

Component manufacturing and end products: EV suppliers cited policy volatility as a driver of demand uncertainty. Data centre component makers have visibility of only six to nine months, while utilities face procurement cycles misaligned with decade-long grid investments, limiting their ability to finance expansions.

Infrastructure

Mining and refining: Access to logistics and utilities is now the critical path for new projects. Multi-billion dollar enabling infrastructure – railways, ports, desalination or power – is often required before production begins. Projects such as the QB2 copper mine expansion[43] in Chile or Simandou[44] in Guinea illustrate how the scope of infrastructure can rival that of the mine itself.

Component manufacturing and end products: Transformer and HV-cable bottlenecks can hold up entire projects. Lead times of one to four years in some markets means EV chargers, data centres and grid upgrades compete for the same equipment.

Resources and energy

Mining and refining: Declining ore grades and tightening power supply raises costs and emissions. Copper grades have fallen 40% since the 1990s,[45] while smelters from Yunnan to Mozambique[46] have faced energy curtailments, thus idling globally relevant assets.

Component manufacturing and end products: Tight supplies of copper, aluminium and electrical steel (GOES) expose all three value chains to shared material risks.

Sustainability and licence-to-operate

Mining and refining: Permitting remains slow and uncertain – a mine can take 18 years or more to commission,[47] and often take up to a decade for approvals. Rising environmental, social and governance (ESG) standards and local opposition can delay projects well before construction begins. Recycling is expanding but still lacks transparency and assurance mechanisms.

Component manufacturing and end products: End-product manufacturers face scrutiny over life-cycle emissions, recyclability and conflict minerals, while grid developers confront land-use constraints and community opposition.

Technology

Mining and refining: Technology cycles are moving faster than new supply chains can adjust. Producers struggle to bet on the "next chemistry" without risking stranded assets, while recycling remains limited by collection and mechanical separation bottlenecks.

Component manufacturing and end products: Battery chemistries and semiconductor designs evolve faster than capacity can respond, creating mismatches between innovation cycles and supply resilience.

Labour and skills

Mining and refining: Shortage of skilled engineers and project specialists increases delays in mine development and processing.

Component manufacturing and end products: EV and grid manufacturers report high demand for chemists, battery engineers and HV technicians, while data-centre developers face digital-skills gaps, especially in AI-related operations.

Today's risks foreshadow a future where chokepoints and fragmented dialogue could limit growth unless coordination improves. Without shared risk awareness, actors work in silos, leaving systemic vulnerabilities unaddressed. The remedy is shared visibility, faster qualification and coordinated commitments.

4 From awareness to action

Building resilience together requires coordinated leadership to align demand, policy and investment – ensuring materials are available when and where needed.

Resilience will not come from firms optimizing alone. Choices in one tier shape timelines and costs across others. Progress depends on strengthened coordination – aligning priorities, mobilizing capital and sequencing action across industries, governments and financiers.

Effective coordination mechanisms – whether local, national or cross-industry – can provide the visibility, legitimacy and capacity to translate plans into delivery. By aligning incentives, standards and investment timelines, they ensure that decisions taken in one part of the system reinforce, rather than compete with, those in another. When this alignment is absent, actions remain fragmented; when it is present, value chains can move in sequence from shared understanding to investment and delivery.

Consultations also showed that companies are taking on new roles as mediators and bridge-builders – creating transparency, sharing information and piloting innovative ways to manage risk and translate policy signals into practical action. Coordination will not “self-organize”. It must be supported by empowered actors, including regional alliances, public-private taskforces and cross-sector partnerships capable of driving progress at their respective levels.

4.1 Lessons from past disruptions

In many cases, supply shocks have triggered coordinated multistakeholder actions. The imperative now is to deploy them proactively to build resilience before risks materialize. Learnings from the consultations and examples of deployed actions (Figure 14) indicate that resilience improves fastest when two things happen in parallel: supply is strengthened and diversified where bottlenecks and concentration are greatest, and demand is managed so that exposure to supply is lower and more flexible.

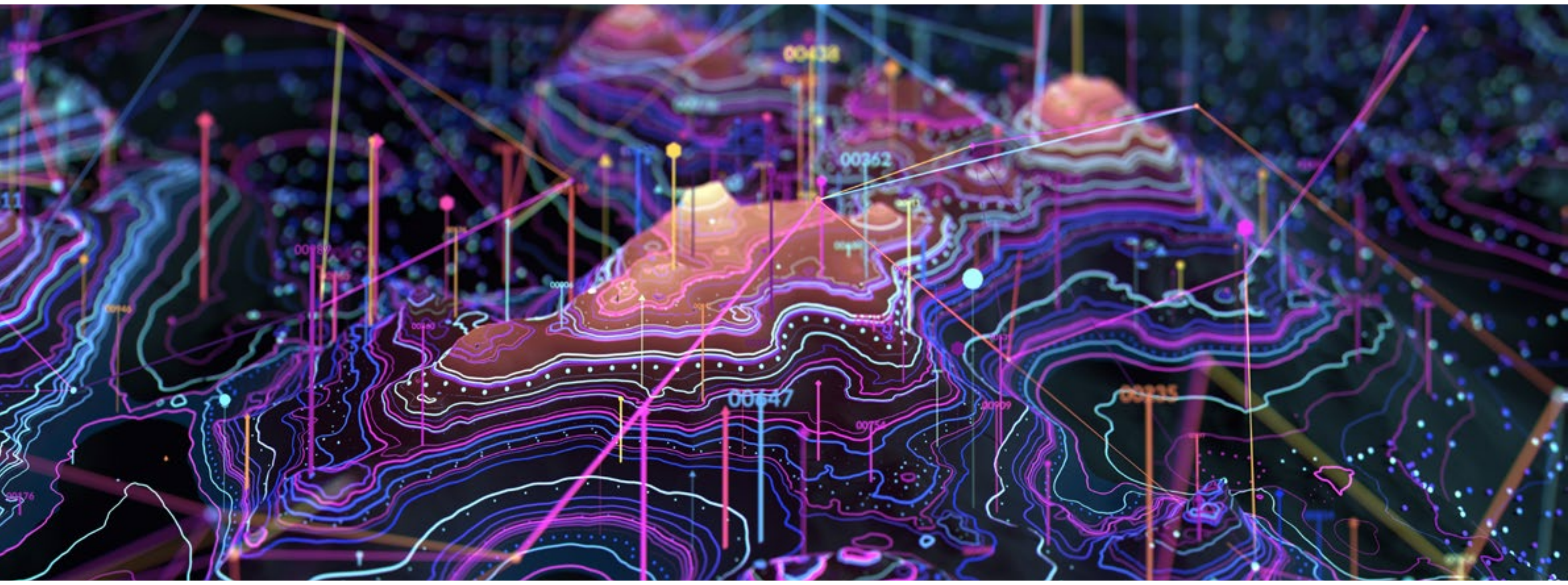


FIGURE 14 | **Examples of collective actions and associated resilience levers**

	Examples of resilience strategies and levers			
Trigger	Supply expansion and diversification		Demand management	
Export controls on REE technologies and REEs (2023, 2025)	**New capacity/public co-financing** US Department of Defense funded mining company Lynas's rare-earth processing and partnered with MP Materials to build a domestic rare-earth supply chain	**Secondary supply infrastructure/ multi-year offtake** Nidec Motor Corporation and Noveon Magnetics entered into a five-year offtake agreement for US-made recycled rare-earth magnets	**R&D for recycling at scale** Western Digital, Microsoft and others partnered to recover and recycle rare earths from hard disk drives (HDDs)	**Mineral-intensity reduction/ efficiency** Tesla announced its next-generation permanent magnet electric motors will contain no rare-earth elements
Automotive chip shortage created awareness on upstream vulnerabilities (2020-22)	**Equity in new supply/joint projects** General Motors (GM) and Lithium Americas established a joint venture to develop the Thacker Pass lithium mine; Ford, Vale Indonesia and Huayou Cobalt formed an equity partnership to develop a nickel-processing project in Indonesia	**Multi-year offtakes** Tesla signed a three-year lithium supply agreement with Piedmont Lithium; GM agreed to a supply and investment arrangement with Controlled Thermal Resources that gives it first-refusal rights on Salton Sea lithium	**Substitution/ chemistry shifts** Battery chemistries have shifted to reduce cobalt reliance, adjusting nickel-manganese-cobalt (NMC) ratios and expanding lithium-iron-phosphate (LFP) models in mass-market segments	**Mineral-intensity reduction/ efficiency** Mineral use in batteries has been lowered by shrinking battery pack sizes and adopting higher-efficiency pack designs (e.g. cell-to-pack/cell-to-chassis, delivering more power per mass
Oil supply crisis (1973-75)	**Accelerated permitting/new supply** The 1973 Trans-Alaska Pipeline Authorization Act expedited approvals for a strategic pipeline to boost US oil supply	**Allied partnerships** The International Energy Agency (IEA) was established in 1974 by OECD members to coordinate a collective response to oil supply disruptions and ensure supply security	**Efficiency standards** The Corporate Average Fuel Economy (CAFE) standards were introduced under the US Energy Policy and Conservation Act of 1975 to curb fossil-fuel demand growth	**Strategic inventories** The US Strategic Petroleum Reserve was established by the 1975 Energy Policy and Conservation Act as an emergency crude stockpile

Taken together, these responses point to a set of practical levers across supply expansion and diversification and demand management that downstream owners, upstream suppliers, financiers and policy-makers can deploy together.

Supply expansion and diversification: Increase, de-risk and re-route supply

1. **New mining and processing/refining capacity:**
   Capacity additions focused where supply concentration is most acute (e.g. synthetic graphite capacity to address export-licensing restrictions,[48] GOES, REE production) and paced to credible, rolling demand signals help manage disruption risk while limiting asset stranding. Location decisions often follow two paths: extending established refining hubs that already host capabilities and linkages, or bringing processing closer to mines to reduce logistics and emissions and build local value. Evaluation of suitable sites can be guided by the Forum's country-readiness framework[49] for manufacturing and supply chains. Supply diversity may also come from new extraction routes (e.g. direct lithium extraction) once proven at scale.

2. **Long-term offtakes, prepayments and equity investments:**
   Deploying long-tenor, volume-flex offtakes, with prepayment or modest equity where needed, helps secure supply through new capacity. These structures close financing gaps and de-risk projects, particularly for processing in diversified locations, while preserving the buyer's ability to adapt to specification changes.

3. **Public co-financing and guarantees:** Blending private commitments with public instruments (guarantees, first-loss, production credits) from national or regional programmes improves project bankability and FID speed, particularly for first-of-its-kind or first-in-region capacity.

4. **Streamlined, predictable permitting and infrastructure enablement:** Treat permitting, interconnection, ports and rail as part of a value chain-critical path. Clear, time-bound processes and early community engagement reduce project delay risk more than design tweaks.

5. **Allied/friend-shoring partnerships and joint projects:** Forming joint ventures and reciprocal offtakes among allied markets spreads geopolitical and logistics risk while keeping scale economics. Further, pairing partnerships with common standards and mutual recognition keeps switching costs low.

6. **Industrialized secondary-supply infrastructure:** Scaling industrial recycling with the same rigour as primary supply can drive additional diversification. Analyses show that over 20% of the current global import demand of a selection of energy transition minerals[50] could be satisfied through recycling.[51]

Demand management: Reshape demand

1. **Efficiency and mineral-intensity reduction:** Design and engineering, through part consolidation, yield improvement or unit optimization, can reduce metal intensity per unit without sacrificing safety or performance. However, consultations also raised a note of caution: ultra-low content can make end-of-life recovery commercially or technically challenging. Designing for performance and circularity in tandem is key.

2. **Fit-for-purpose substitution:** Where performance and safety requirements allow, changing materials, chemistries and components can reduce pressure on scarce inputs; for example, using LFP batteries or REE-free motors in appropriate EV segments, installing aluminium conductors in place of copper where grid specifications permit, or leveraging silicon-carbide/gallium nitride power devices in data centres to raise efficiency with a different materials mix.

3. **Recycling and circularity at scale:** Building secondary supply from end-of-life products and manufacturing scrap (e.g. battery-grade salts from battery “black-mass,” copper and aluminium scrap capture) shifts demand patterns. Recycling today contributes a small share for several critical minerals: end-of-life recovery for lithium and REEs remains below 5% globally, constrained by collection, economics and technology. Consultations stressed the immediate bottleneck is collection and mechanical separation; therefore, this should be a key area of focus.

4. **Strategic inventories and buffers:** Targeted buffers at the right tier (e.g. active materials, trade-restricted metals) can prevent long production stoppages. Approaches range from strategic public stockpiles to private vendor-managed inventory with transparent draw-down rules and replenishment triggers.

5. **Standards and interoperability:** Agreeing on common standards and modular designs (e.g. fewer chip variants, standardized transformer specifications, clear efficiency targets, harmonized audit requirements) enables a shift in demand structure, simplifies manufacturing requirements, incentivizes R&D that reduces mineral intensity and avoids duplicative audits.

4.2 Making coordination possible

No firm can secure minerals alone. Deep interdependencies require coordinated de-risking, with policy-makers creating the conditions for private investment and innovation.

Three enablers consistently emerged in consultations:

- **Convening platforms:** Regular, mandate-backed forums where stakeholders across value chains share market perspectives, surface bottlenecks and act; for example, cross-tier roundtables to discuss supply requirements and constraints or multi-industry consortia where single sectors lack scale (e.g. wind energy and automotive players for REE-magnets).

- **Information transparency tools:** Mechanisms for non-sensitive data sharing that improves market understanding without breaching commercial sensitivities; for example, projections on global mineral production and capacity to provide data-backed understanding of potential future supply availability.

- **Standards:** Converging on traceability and qualification baselines to eliminate duplicative audits and shorten time-to-supply; alignment is already advancing (e.g. London Metal Exchange-recognized standards, battery-passport pilots, the Consolidated Mining Standard Initiative led by Copper Mark, International Council on Mining and Metals, Mining Association of Canada and World Gold Council). However, mutual recognition and data interoperability are still in progress.

4.3 Roadmap to delivery

Resilience across mineral and metal value chains requires decisive leadership, clear ownership, a multi-year iterative effort to turn plans into delivery and a cadence to measure progress and adapt.

Based on consultations and the above analysis, this roadmap outlines a pragmatic starting point to achieve that goal: defining distributed leadership, effective coordination and collective delivery.

Step 1

Strengthening coordination capacity: Resilience depends on credible alignment across complex, multi-tier value chains. Rather than a single orchestrator, progress will emerge through multiple coordination hubs – public-private alliances, regional partnerships and industry-led initiatives, which can align incentives, mobilize resources and sustain collaboration over time.

An effective coordination mechanism brings together a distinct set of capabilities:

- **Visibility:** A system-wide view of flows, capacities and risks, supported by transparent and reliable data.

- **Legitimacy and trust:** The credibility to convene actors across tiers, finance and government.

- **Influence and scale:** The ability to shape standards, investment priorities and policy frameworks that drive collective outcomes.

- **Execution capability:** Resources and discipline to move from coordination to delivery, with clear milestones and progress metrics ensuring that commitments translate into results.

- **Technology enablement:** Use of digital tools such as AI, digital twins and predictive analytics to strengthen foresight and responsiveness.

Few actors combine these capabilities, but several existing mechanisms already demonstrate what distributed coordination can look like – such as the EU's CRMA, the Global Battery Alliance (GBA) or the International Resource Panel's call for an International Minerals Agency. These efforts illustrate how sectoral, regional or thematic alliances can complement one another to improve system-wide resilience.

Building this capacity for coordination, anchored in local realities but connected through shared standards and information frameworks, is essential to move from fragmented initiatives to cumulative global progress.

Step 2

Building shared visibility: A common fact base is needed to clarify vulnerabilities, interdependencies and timing gaps across value chains.

- **Develop joint risk maps** to identify critical bottlenecks, interlinked exposures and timing mismatches across sectors. These maps can guide prioritization, highlight where coordination is most urgent and set baselines for tracking improvements over time.

- **Create collective resilience frameworks** to align investments and policies to add capacity where it delivers the most impact.

Step 3

Defining strategies to collectively build resilience: Once a shared picture is established, stakeholders can translate it into coordinated strategies.

- **On the supply side:** Diversification, long-term offtakes, public co-financing and streamlined permitting increase capacity and optionality.
- **On the demand side:** Engineering efficiency, material substitution and circularity reduce exposure to primary supply.

Step 4

Creating enablers for collective action: Three mechanisms are critical.

- **Convening platforms:** Regular, mandate-backed forums for information exchange, joint problem-solving and progress tracking against shared metrics.
- **Information-transparency tools:** Non-sensitive data sharing to improve market visibility and inform decisions without breaching confidentiality.
- **Standards and interoperability:** Harmonized frameworks to cut friction and accelerate supply readiness.

Together, these steps form a pathway from shared risks to delivery. Coordination across value chains is the catalyst to align priorities, accelerate execution and embed resilience system-wide.

Conclusion

This white paper set out to (1) make minerals dependencies visible across the EVs, data centres and ET&D supply chains; (2) identify where and how risks translate into delivery delays and cost inflation; and (3) offer an approach for a successful collective action agenda that downstream owners, upstream suppliers, financiers and policy-makers can execute together. Across analysis and consultations, five conclusions stand out.

1. **The system is interdependent by design and exposed by concentration.**
   All three value chains share multi-tier structures and overlapping materials. Mining is more geographically dispersed, but refining and processing are concentrated in a few hubs, making them the dominant choke points. Disruptions at these hubs – whether by export controls, power shortages, extreme weather or logistics – propagate to component factories and downstream commissioning schedules.

2. **Timing, not just tonnage, is the binding constraint.**
   Meeting 2035 demand requires a step-change in capacity, much of it still at planning or earlier stages. Mines need decades from discovery to first ore; processing plants take three to eight years to build and qualify; equipment factories ramp in one to five years. Without advanced signals and coordinated planning, even well-resourced programmes will deliver too late.

3. **Risk is multi-dimensional and today's pain points are instructive.**
   Seven vectors recur across tiers and value chains: geopolitics and trade, market/finance, infrastructure, resources and energy, sustainability and licence-to-operate, technology and labour and skills. Their interaction explains today's pain points and why shocks cascade. EV makers reacted first because of learnings from the semiconductor shock, providing an approach others can adapt.

4. **Supply and demand have to be managed in parallel.**
   Resilience improves fastest by expanding supply and reducing demand exposure – approaches proven during past shocks. On the supply side, offtakes, co-financing, streamlined permitting and secondary supply expand and de-risk capacity. On the demand side, efficiency, substitution, recycling and standards lower exposure and speed up qualification.

5. **Resilience is a collective endeavour.**
   It will rely on distributed coordination across governments, industries and investors, each contributing within its scope. Regional partnerships, sectoral alliances and cross-value chain collaboration can together strengthen transparency, predictability and investment confidence. Governments play a pivotal role through predictable permitting, infrastructure enablement and targeted co-financing where markets alone under-deliver. To enable such collective progress, regular dialogue platforms, non-sensitive information-sharing tools and harmonized standards are critical foundations for success.

Mineral resilience is not just about raw-material availability. It's also about timely delivery of vehicles, data capacity and grid connections that sustain growth and the energy transition. Open, predictable trade keeps materials flowing efficiently and builds investor confidence. No region can secure this alone. Coordinated demand, predictable permitting and diversified supply can turn systemic fragility into reliability. The imperative now is to organize, sequence and execute together – using the guiding roadmap above to align time horizons across tiers, set and report shared resilience metrics, and coordinate across borders.

The World Economic Forum will continue facilitating dialogue across mining, processing, manufacturing and policy, to raise awareness about the risks impacting mineral-intensive value chains and providing a space to support the incubation of coordinated actions that strengthen their resilience.

Contributors

World Economic Forum

Sarah Adam
Project Fellow, Future-Proofing Global Value Chains, Centre for Advanced Manufacturing and Supply Chains

Tatiana Aguilar
Manager, Mining and Metals Industry, Global Industries Team

Memia Fendri
Content Curation and Operational Excellence Lead, Centre for Advanced Manufacturing and Supply Chains

Kearney

Artem Botinov
Partner

Per Hong
Partner, Kearney Foresight Global Lead

Tom Balteau
Senior Business Analyst

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Yun B. Choi
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Chief Executive Officer, Newmont

Jonathan Price
President and Chief Executive Officer, Teck Resources; Mining and Metals Industry Community Chair

Jeremy Weir
Chairman, Trafigura Group

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World Economic Forum

Kiva Allgood
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Francisco Betti
Head, Global Industries Team; Member of the Executive Committee

Fernando Gómez
Head, Future of Materials, Centre for Energy and Materials; Member of the Executive Committee

Eleni Kemene
Lead, Materials Systems, Centre for Energy and Materials

Anis Nassar
Manager, Materials Systems, Centre for Energy and Materials

Kearney

Romain Debarre
Partner, Energy Transition Institute Managing Director

Suketu Gandhi
Partner and Chair, Strategic Operations

Angela Hultberg
Global Sustainability Director

Nina Jabari
Graphic Designer

Bontle Mahoda
Senior Business Analyst

Harris Ng
Partner, Automotive and Industrials

Jerome Sevin
Partner, Energy and Process Industries Global Lead

Production

Madhur Singh
Editor

Jean-Philippe Stanway
Graphic Designer

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org