The **Barriers to Clean Electrification** Series

Material and Resource Requirements for the Energy Transition

July 2023

Version 1.0

Energy Transitions Commission

Materials and Resource Requirements for the Energy Transition

The Energy Transitions Commission (ETC) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C.

Our Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. The ETC is chaired by Lord Adair Turner who works with the ETC team, led by Faustine Delasalle (Vice-Chair), Ita Kettleborough (Director), and Mike Hemsley (Deputy Director).

The ETC's *Material and Resource Requirements for the Energy Transition* was developed by the Commissioners with the support of the ETC Secretariat, provided by Systemiq. This report constitutes a collective view of the Energy Transitions Commission. Members of the ETC endorse the general thrust of the arguments made in this publication but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse this report.

Accompanying this report, the ETC has developed a series of Material Factsheets for key materials (cobalt, copper, graphite, lithium, neodymium and nickel), available on the ETC website.

This report looks to build upon a substantial body of work in this area, including from the IEA, IRENA, and ETC knowledge partners BNEF and RMI.

The ETC team would like to thank the ETC members, member experts and the ETC's broader network of external experts for their active participation in the development of this report.

The ETC Commissioners not only agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by mid-century but also share a broad vision of how the transition can be achieved. The fact that this agreement is possible between leaders from companies and organisations with different perspectives on and interests in the energy system should give decision-makers across the world confidence that it is possible simultaneously to grow the global economy and to limit global warming to well below 2°C. Many of the key actions to achieve these goals are clear and can be pursued without delay.

Learn more at:

www.energy-transitions.org

www.linkedin.com/company/energy-transitions-commission

www.twitter.com/ETC_energy

www.youtube.com/@ETC_energy

Barriers to Clean Electrification Series

The ETC's *Barriers to Clean Electrification* series focuses on identifying the key challenges facing the transition to clean power systems globally and recommending a set of key actions to ensure the clean electricity scale-up is not derailed in the 2020s. This series of reports will develop a view on how to "risk manage" the transition – by anticipating the barriers that are likely to arise and outlining how to overcome them, providing counters to misleading claims, providing explainer content and key facts, and sharing recommendations that help manage risks. Previous publications in this series include ETC (2023), *Streamlining planning and permitting to accelerate wind and solar deployment* and ETC (2023), *Better, Faster, Cleaner: Securing clean energy technology supply chains.*

The Energy Transitions Commission is hosted by SYSTEMIQ Ltd.

Front cover Image: Aerial view of an open-pit copper mine in Peru (Jose Luis Stephens/Shutterstock.com).

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Major ETC reports and working papers

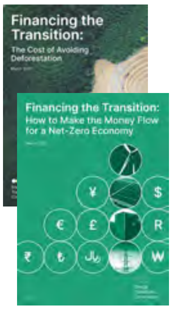
Global Reports

Mission Possible (2018) outlines pathways to reach net-zero emissions from the harder-to-abate sectors in heavy industry (cement, steel, plastics) and heavy-duty transport (trucking, shipping, aviation).

Making Mission Possible (2020) shows that a net-zero global economy is technically and economically possible by mid-century and will require a profound transformation of the global energy system.

Making Mission Possible Series (2021–2022) outlines how to scale-up clean energy provision to achieve a net-zero emissions economy by mid-century.

Keeping 1.5°C Alive Series (2021–2022) COP special reports outlining actions and agreements required in the 2020s to keep 1.5°C within reach.



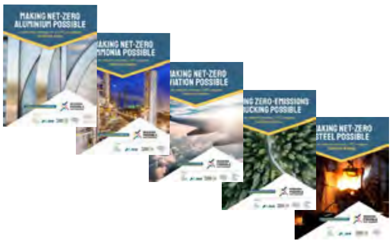
Financing the Transition (2023) quantifies the finance needed to achieve a net-zero global economy and identifies policies needed to unleash investment on the scale required.

Barriers to Clean Electrification Series (2022–2024) recommends actions to overcome key obstacles to clean electrification scale-up, including planning and permitting, supply chains and power grids.

Sectoral and cross-sectoral focuses

Sectoral focuses provided detailed decarbonisation analyses on six of the harder-to-abate sectors after the publication of the **Mission Possible** report (2019).

As a core partner of the MPP, the ETC also completes analysis to support a range of sectorial decarbonisation initiatives:



MPP Sector Transition Strategies (2022–2023) a series of reports that guide the decarbonisation of seven of the hardest-to-abate sectors. Of these, four are from the materials industries: aluminium, chemicals, concrete, and steel, and three are from the mobility and transport sectors – aviation, shipping, and trucking.

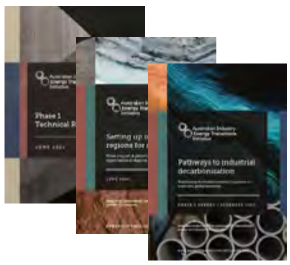
Unlocking the First Wave of Breakthrough Steel Investments (2023) This ETC series of reports looks at how to scale-up near-zero emissions primary (ore-based) steelmaking this decade within specific regional contexts: the UK, Southern Europe, France and USA.

Geographical focuses

China 2050: A Fully Developed Rich Zero-carbon Economy (2019) Analyses China's energy sources, technologies and policy interventions required to reach net-zero carbon emissions by 2050.

A series of reports on the Indian power system, outlining decarbonisation roadmaps for India's electricity supply and heavy industry.

Canada's Electrification Advantage in the Race to Net-Zero (2022) identifies 5 catalysts that can serve as a starting point for a national electrification strategy led by Canada's premieres at the province level.



Setting up industrial regions for net zero (2021–2023) explore the state of play in Australia, and identifies opportunities for transitioning to net-zero emissions in five hard-to-abate supply chains.

Glossary

BEV or EV: (Battery) electric vehicle.

Bioenergy: Renewable energy derived from biological sources, in the form of solid biomass, biogas or biofuels.

Bioenergy with carbon capture and storage (BECCS): A technology that combines bioenergy with carbon capture and storage to produce energy and net negative greenhouse gas emissions, i.e. removal of carbon dioxide from the atmosphere.

Carbon capture and storage (CCS): The term "carbon capture" is used to refer to process of capturing CO_2 on the back of energy and industrial processes. The term "carbon capture and storage" refers to the combination of carbon capture with underground geological storage of carbon.

Carbon emissions/CO_2 emissions: These terms are used interchangeably to describe anthropogenic emissions of carbon dioxide into the atmosphere.

Direct Air Carbon Capture (DACC): The term used for various technologies which use chemical processes to separate carbon dioxide from the atmosphere. This term does not carry any implications regarding subsequent treatment of the captured carbon dioxide, i.e. it could be utilised or stored.

Electrolysis: A technique that uses electric current to drive an otherwise non-spontaneous chemical reaction. One form of electrolysis is the process that decomposes water into hydrogen and oxygen, taking place in an electrolyser and producting "green" hydrogen. This process can be zero-carbon if the electricity used is zero-carbon.

Environmental impacts: Harmful effects of human activities on ecosystems and natural resources. These include climate change impacts (through greenhouse gas emissions), ecotoxicity impacts, land-use related biodiversity loss, and water stress.

FCEV: Fuel-cell electric vehicle.

Greenhouse gases (GHGs): Gases that trap heat in the atmosphere. Global GHG emission contributions by gas are roughly 76% CO_2, 16% methane, 6% nitrous oxide, and 2% fluorinated gases.

Materials: A sub-set of resources that include biomass, fossil fuels, metals and non-metallic minerals. In this report we focus on a set of metals that are highly relevant to the energy transition and are interchangeably referred to as "energy transition materials", "energy transition metals", or "critical raw materials". (See also Primary and Secondary Materials.)

Materials efficiency: Using less materials to provide the same level of performance for a given technology, typically in units of mass (kg) per installed capacity (MW or MWh).

Mineral Reserves: A dynamic working inventory of economically-extractable minerals/commodities that are currently recoverable.

Mineral Resources: The total amount of a mineral/commodity that is geologically available in sufficient concentrations that extraction is potentially feasible. Typically used to refer to materials available on land (i.e. excluding deep-sea resources).

Natural Climate Solutions (NCS): "Conservation, restoration and/or improved land management actions to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, agricultural lands and oceans".[1] This can be coupled with technology to secure long-term or permanent storage of greenhouse gases.

Natural Resources: These include land, water and materials, and are parts of the natural world that can be used in economic activities to produce goods and services.

Ore: Natural rock or sediment deposits that contains one or more valuable minerals.

Ore grade: The percentage of an element of interest within a potentially mineable ore. The ore grade of different metals vary considerably, e.g., around 50% for iron ore or around 0.6% for copper ore.

Primary Materials: Materials that have been extracted from the natural environment, typically through mining.

Rare Earth Elements (REEs): A set of seventeen metallic elements, made up of the fifteen lanthanides, as well as scandium and yttrium. This report focuses on the neodymium, a rare earth element typically used in high-strength magnets in both wind turbines and electric vehicles.

Secondary Materials: Materials that have been recycled from a previous use-case and are supplied back into the economy as "new" raw materials.

Tailings: This is the ground rock residual that remains following any milling or beneficiation processes which removes the valuable metallic constituents from the mined ore.

Waste Rock: This is rock that has been mined and transported out of a mine pit, but does not contain metal concentrations of economic interest. Sometimes referred to as "overburden".

1 Griscom et al. (2017), *Natural climate solutions*.

Contents

Introduction

The Paris Climate Accord committed the world to keeping global warming to well below 2°C from pre-industrial levels, aiming ideally for a 1.5°C limit. To have a 90% chance of staying below 2°C and a 50% chance of limiting warming to 1.5°C, the world must reduce CO_2 and other greenhouse gases to around zero by mid-century, with a reduction of around 40% achieved by 2030. The ETC supports these objectives and believes that all high-income countries should reach net-zero by 2050 at the latest, and all middle- and lower-income countries by 2060.

Achieving this will require the rapid and large-scale rollout of multiple clean energy technologies, of which the most important support the massive expansion and complete decarbonisation of electricity supply, a deep electrification of most energy final uses, and a hugely expanded role for low-carbon hydrogen, primarily produced via electrolysis ("green hydrogen"). Total electricity supply will need to rise from today's roughly 30,000 TWh to over 100,000 TWh by mid-century; green hydrogen production could reach 500–800 Mt per annum; transmission and distribution grids will need to expand from around 70 million kilometres to up to 200 million kilometres; and 1.5 billion passenger electric vehicles (EVs) would require around 100 TWh of aggregate battery capacity.

Building this new clean energy system will require a wide range of critical raw materials, from copper for wiring, steel for wind turbine towers, rare earth elements for electric motors, lithium, nickel and graphite for batteries, and silicon for solar photovoltaic (PV) panels. Supplying these materials will require large scale investments and rapid expansion of mining and refining capacity. At the same time, coal production would have to decrease more than 90% from current levels as the energy transition unfolds.[2]

This ETC report builds upon existing work and assesses:[3]

- Whether there are sufficient raw material resources to support the energy transition.
- Whether supply can grow fast enough to meet demand.
- The global and local environmental impacts of increased mining and metals refining.
- The actions which can be taken to ensure adequate and secure supply and to reduce adverse environmental impacts.

The key conclusions are that:

- The new clean energy system has **manageable requirements** for land, water and materials – and will lead to **drastically lower emissions**, helping to reach net-zero emissions and avoid future climate change and its impacts.
- Over the long term, there are **sufficient resources** of all the raw materials (and of land area and water) to support the energy transition, and in those cases where currently assessed "reserves"[4] fall short of potential cumulative demand – in particular copper and nickel – reserve expansion can and will be achieved.
- There is major potential to reduce future cumulative demand for energy transition materials via **technical innovation and recycling**, which should be strongly supported and required by public policy.
- **Mining will need to expand.** Scaling supply rapidly enough to meet demand growth between now and 2030 will be challenging for some metals, in particular lithium, copper, nickel, cobalt, graphite and neodymium; but actions can be taken by governments and companies which would prevent any serious constraint on the pace of the energy transition.
- Mining can expand in a **sustainable and responsible** way.
  - The adverse global and local environmental impacts of extracting the materials and minerals required for a clean energy system are far less than those imposed by the extraction and use of fossil fuels. Shifting from use of **consumable fossil fuels** which must be continuously extracted to the use of **durable metals** which can be reused and recycled, creates a fundamentally more sustainable energy system.
  - Mineral extraction and refining does currently have significant **impacts on local environments and communities.** However, these can be minimised through best practise responsible mining, which should be required by strong regulation.

2 Coal production would be approximately 650 Mt p.a. in 2050 (accounting for both thermal coal for power generation and metallurgical coal for steel) compared to existing levels of over 8,000 Mt p.a. The ETC will be covering this topic in detail in an upcoming report on fossil fuels. Systemiq analysis for the ETC, based on ETC (2020), *Making mission possible*; ETC (2022), *Mind the gap*; IEA (2021), *Net zero by 2050: A roadmap for the global energy sector*; BP (2023), *Energy Outlook – Net zero scenario*; Shell (2021), *Energy transformation scenarios – Sky scenario*; BNEF (2022), *New energy outlook – Net Zero Scenario.*

3 See e.g., ETC (2023), *Better, faster, cleaner: Securing clean energy technology supply chains*; IEA (2022), *The role of critical minerals in clean energy transitions*; World Bank (2020), *Minerals for Climate Action*; WWF/SINTEF (2022), *Circular Economy and Critical Minerals for the Green Transition*; Watari et al. (2019), *Total material requirements for the global energy transition to 2050: A focus on transport and electricity.*

4 The economically and technically exploitable subset of typically larger resources – see Box A.

The report covers in turn:

1. The availability and sufficiency of natural resources for an inherently more sustainable energy system.
2. Projections of demand and supply to 2030 and the potential to reduce demand through technical innovation and recycling.
3. Challenges facing rapid supply ramp up and action to ensure adequate and secure supply.
4. Global and local environmental impacts and actions to reduce them.
5. Summary actions for industry and policy makers in the next decade.

This report is accompanied by a set of Material Factsheets, covering key information for six priority energy transition materials: cobalt, copper, graphite, lithium, neodymium and nickel. A short Executive Summary of this report is also available.

Energy Transitions Commission

MATERIAL AND RESOURCE REQUIREMENTS FOR THE ENERGY TRANSITION

The clean energy system in 2050

ENERGY TECHNOLOGIES (Scale-up needed)	WIND	SOLAR	POWER GRID	GREEN HYDROGEN	EVs AND BATTERIES	CARBON CAPTURE
2022	1 TW	1.2 TW	70 Million Km	<1 MT	25 M EV FLEET	0.05 $GtCO_2$ p.a.
Scale-up	x15	x25	x3	x500	x60	x100
2050	14-15 TW	26-34 TW	200 Million Km	500-800 MT	1500 M	7-10 $GtCO_2$ p.a.

Deploying clean energy technologies will require a range of materials

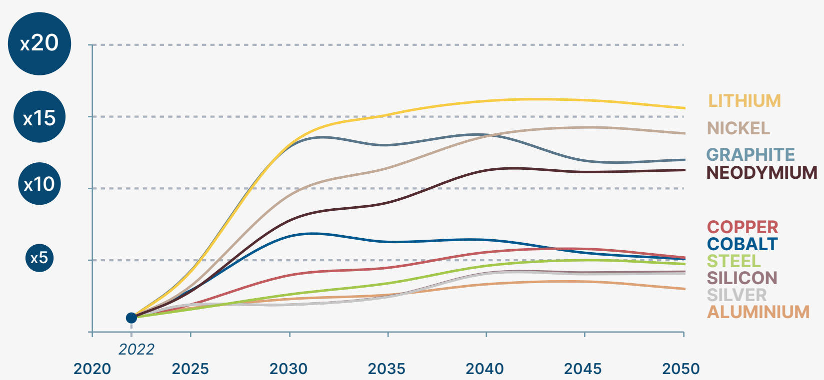
KEY MATERIAL NEEDS

- ENERGY TRANSITION MAIN DRIVER OF DEMAND
- OTHER SECTORS MAIN DRIVERS OF DEMAND
- A MIX OF BOTH

	WIND	SOLAR	POWER GRID	GREEN HYDROGEN	EVs AND BATTERIES	CARBON CAPTURE
All technologies	ALUMINIUM AND STEEL					
All technologies	COPPER					
	NICKEL, NEODYMIUM	POLYSILICON, SILVER		NICKEL, PLATINUM & PALLADIUM	NICKEL, NEODYMIUM, LITHIUM, COBALT, GRAPHITE	SORBENT CHEMICALS E.G. MONOETHANOLAMINE

REQUIRED SCALE-UP IN MATERIALS DEMAND BY 2050

Relative increase in demand for key materials from clean energy technologies, from 2022



MATERIALS

SUFFICIENT GLOBAL RESOURCES

Million metric tonnes

A clean energy system will have manageable resource requirements for land and water - and lead to **drastically lower emissions.**

WATER USE - ANNUAL

4,000 *bn m³ of global annual water consumption*

Agriculture **70%**
2,700 *bn m³*

Clean Energy **<2%**
58 *bn m³*

Fossil Fuels **~1%**
37 *bn m³*

LAND USE - TOTAL

106 *m Km² of global habitable land*

Agriculture **~50%**
51 *Million km²*

Clean Energy **<1%**
0.75 *Million km²*

Fossil Fuels **<1%**
0.3 *Million km²*

GLOBAL EMISSIONS - 2022-2050

~**1000** *$GtCO_{2e}$ emissions from* **fossil fuels**

+ *continuing indefinitely*

≤ 40 $GtCO_{2e}$

*Emissions from producing **all** of the materials needed for a **clean energy** system.*

Emissions will fall to zero as mining and manufacturing decarbonise.

Energy Transitions Commission

SIX KEY MATERIALS FOR THE ENERGY TRANSITION

There are more than enough materials on earth to meet demands for the energy transition...

...but ramping up supply fast enough this decade to decarbonise the global economy by 2050 will be challenging.

Concerted action is required to:

- Reduce primary material requirements through innovation and recycling
- Rapidly increase mining in a sustainable and responsible way

PROJECTED DEMAND AND SUPPLY IN 2030

Million metric tonnes

2022	2030		
Supply	Max Primary Demand [1]	Min Primary Demand [2]	Estimated Supply [3]

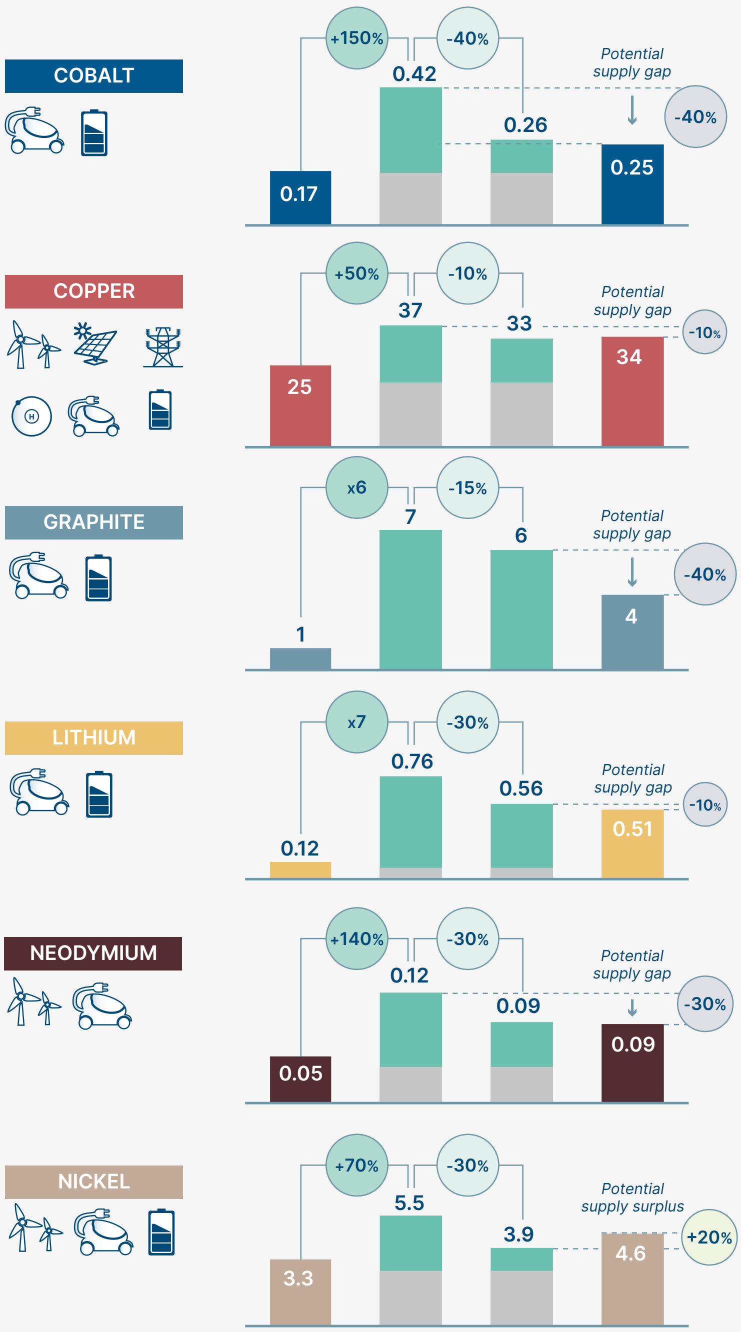
Primary demand for the energy transition

Demand for other uses

[1] Max demand: Upper bound of material requirements for rapid decarbonisation

[2] Min demand: Material requirements with greater material / technology efficiency and recycling

[3] Estimated supply: mining forecasts 2030 based on current plans



Key Considerations

Cobalt
- Trend away from cobalt-rich batteries will ease supply imbalances.
- High potential to increase recycling from EV batteries.
- Uncertainty over supply from DRC (~70% of market + concerns around human rights), but strong supply growth from Indonesia.

Copper
- High prices will incentivise thrifting or substitution, but widespread need limits potential for large demand reductions.
- Declining production from existing mines, falling ore grades.
- Up to 20 years for new large mines to come online.

Graphite
- Supply dominated by China, but new projects in US, Africa.
- Additional synthetic graphite supply could close supply gaps, but has high carbon intensity.
- In the long-term, high potential to substitute with silicon or lithium in anodes and for recycling.

Lithium
- Relatively faster timelines for new mines (4-7 years).
- Sodium-ion batteries can reduce lithium demand from 2030 – but likely to be small share of market.
- High potential for recycling over long term.
- Concerns around water and carbon intensity of production.

Neodymium
- Potential to reduce material intensity and shift to neodymium-free motors.
- Supply heavily concentrated in China, but potential new supply in Myanmar, USA, Australia.
- Mining and refining generate large volumes of toxic waste and historically poorly regulated.

Nickel
- Fast increase in supply feasible with growth of mining in Indonesia – but current production is carbon intensive.
- Challenges to supply high quality Class 1 nickel and refined nickel sulphate for battery cathodes.
- Strong potential to shift away from nickel-rich batteries.

Energy Transitions Commission - July 2023

Chapter 1

Sufficient natural resources for an inherently more sustainable energy system

There are easily sufficient resources and materials available to support the needs of a global net-zero economy and deliver widespread prosperity. This net-zero economy will, over the long-term, impose a dramatically lower impact on the world's atmosphere and environment than today's fossil fuel based system by avoiding climate change and transitioning to a new system of largely one-off materials extraction.

In a series of reports over the past six years, the ETC has described the technologies and investments required to build a global net-zero economy which can deliver widespread prosperity across the world.[5]

Key features include [Exhibit 1.1]:[6]

- **A dramatic increase in global electricity use**, rising from 28,000 TWh in 2022 to reach as much as 110,000 TWh by 2050. Over 75% of this would be supplied by wind and solar, requiring around 26–34 TW of solar and 14–15 TW of wind, up from around 1.2 TW and 1 TW, respectively, today. The rest will be provided by a mix of nuclear, hydropower and other zero-carbon sources, along with battery and other storage to support around 5% of daily generation needs.

- **A major expansion of electricity grids**, expanding from the current 75 million km of transmission and distribution to over 200 million km by 2050.

- **A major role for low-carbon hydrogen**, with total hydrogen use growing from today's 90–100 Mt (of which only around 1 Mt is low-carbon) to 500–800 million tonnes per annum, of which the strong majority (e.g., 85%) is likely to be "green" hydrogen made via electrolysis powered by low-carbon electricity. This requires electrolyser capacity of up to 7,000 GW in 2050.

- **The near-total decarbonisation of the global passenger vehicle fleet by 2050**, requiring over 1.5 billion electric cars and ~200 million electric trucks and buses. This requires a total battery capacity of up to 150 TWh.

- **Carbon capture, utilisation and storage capacity of around 7–10 GtCO_2 per annum**, to offset remaining fossil fuel use and process emissions in specific applications and deliver carbon removals.

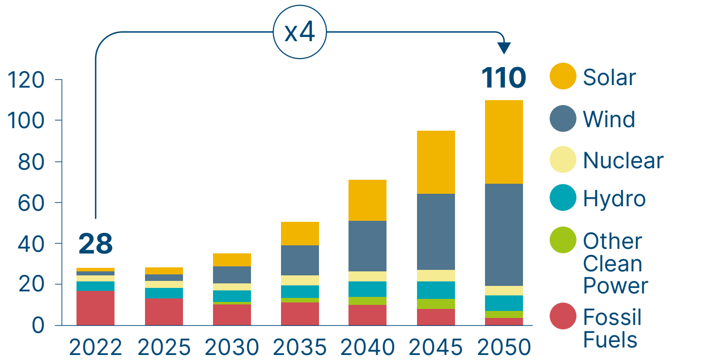
5 ETC (2020), *Making Mission Possible*; ETC (2021), *Making Clean Electrification Possible*; ETC (2021), *Making the Hydrogen Economy Possible*; ETC (2022), *CCUS in the energy transition: vital but limited.*

6 Ranges across technologies here depend on total energy demand in 2050, the share of electricity generated by wind and solar, efficiency of grid build-out and demand for clean hydrogen and efficiency of its production via electrolysis.

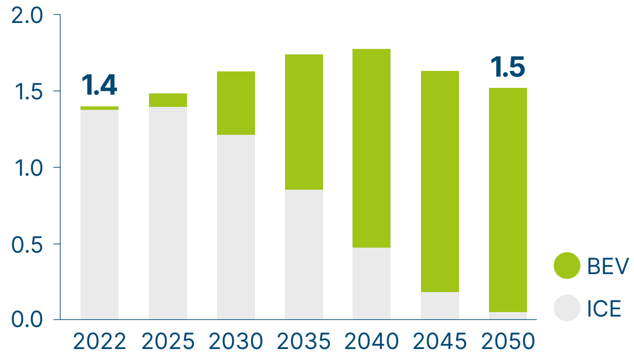
EXHIBIT 1.1

Rapid decarbonisation requires a major ramp-up of a range of clean energy technologies

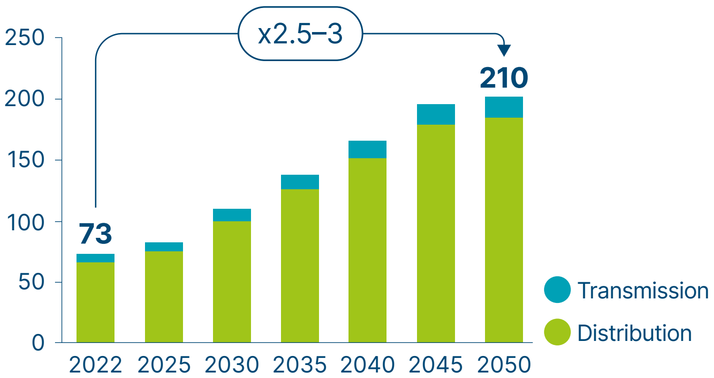
Electricity generation
1000s of TWh/year



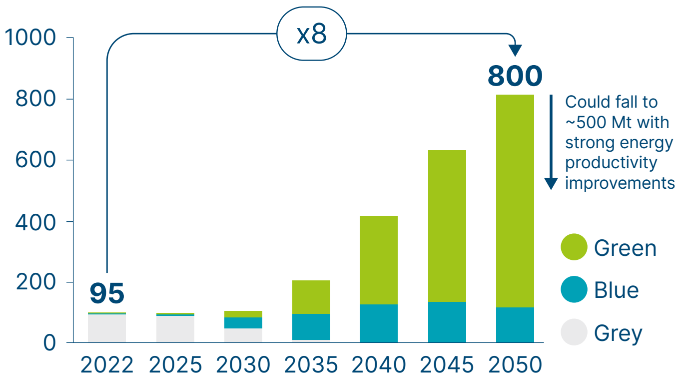
Passenger vehicle fleet
Billions of vehicles



Total transmission and distribution power line length
Millions of km



Hydrogen production
Mt/year



SOURCE: SYSTEMIQ analysis for the ETC; ETC (2021), *Making Clean Electrification Possible*; ETC (2021), *Making the Hydrogen Economy Possible*; BNEF (2023), *Interactive data tool – Generation*; IEA (2022), *Global hydrogen review*; BNEF (2023), *New energy outlook: Grids*; BNEF (2022), *Long-term electric vehicle outlook.*

Building, operating and maintaining this clean energy system will require large-scale natural resource and material inputs including:[7]

- Land to site solar and wind farms and grow biomass.
- Water for mining, power generation and as an input to hydrogen electrolysis.
- Materials and metals to build solar and wind farms, batteries, electrolysers, power grids and other clean energy technologies.

This report concentrates primarily on the materials and minerals required, but in this chapter we also assess the land and water requirements to support a net-zero economy based primarily on clean electricity. When considering these requirements, it is important to keep in mind how they compare to the counterfactual of indefinitely continuing today's fossil fuel energy system, and to current requirements in the global agriculture sector.

7 The International Resource Panel (IRP (2019), *Global Resources Outlook* defines resources as land, water and materials, which are part of the natural world that can be used in economic activities to produce goods and services. Materials are a sub-set of resources that include biomass, fossil fuels, metals and non-metallic minerals. In this report, we focus on a set of metals that are highly relevant to the energy transition and are interchangeably referred to as "energy transition materials", "energy transition metals", or "critical raw materials". When considering the resources and reserves of minerals available to meet material demand, this report focuses on those that are available on land.

Most importantly, it is crucial to understand that any impacts on land and water to build and operate a clean energy system will be significantly less than the adverse impacts that will arise from temperature rises above 1.5°C and beyond 2°C in the absence of a rapid energy transition by 2050.

This section therefore covers in turn:

1. Land and water requirements to operate and maintain a clean energy system.
2. Material and mineral requirements compared with globally available resources.
3. The new system vs. the old: a dramatically reduced impact on the global environment over the long-term.

1.1 Land and water requirements for a clean energy system

Total land and water requirements for the global energy system are small compared to other major uses such as agriculture. This section outlines land and water requirements to build and maintain a clean energy system, compared to a fossil fuel energy system.

- **Land** requirements for a zero-carbon energy system are much larger than for a fossil fuel based system, but are small relative to agricultural use and total available land – likely less than 2% of land dedicated to agriculture. In many cases low-carbon energy can be sited on working agricultural land.
- **Water** requirements for metals mining, cleaning solar panels, nuclear power generation, carbon capture and electrolysis for hydrogen could be as much as 1.5–2 times larger than a fossil fuel energy system, but requirements are around 50 times lower than for agriculture.

The required land and water for mining the materials needed to build clean energy technologies is discussed in more detail in Chapter 4.

It is also worth remembering the adverse impacts climate change would have on land and water, which would be avoided with the energy transition. These impacts, outlined in Section 1.3 below, would likely be significantly worse than the requirements to build and operate a clean energy system – whether from water scarcity or available land.[8]

1.1.1 Land requirements for a clean energy system

Exhibit 1.2 sets out the land requirements for a net-zero energy system compared with a fossil fuel system and global agriculture use. Key points are:

- Land requirements for **wind and solar**, including power generation for direct electricity use, green hydrogen production, and direct air carbon capture (DACC), account for around 0.4–1.1 million square kilometres of land[9] – around 1% of global land use and an area of land slightly less than current urban areas.[10] Importantly, the impact on global biodiversity or agriculture is much less than this would imply, given that:
  - Much solar photovoltaic (PV) can be placed on rooftops or on desert and other land which is unsuitable for agriculture – around 40% of solar PV installations in 2021 were on rooftops.[11]
  - Wind farms compete only minimally with agricultural land use, and solar farms can also be combined with some agricultural activity and biodiversity.
- The largest land requirements for renewable energy – and the biggest potential adverse impact on biodiversity – derives not from wind and solar deployment, but from **bioenergy production**. But sustainable use of bioresources

8 For example, the IPCC estimates that one-quarter of the world's natural land now experiences longer wildfire seasons, and that at 2°C of warming land that is currently used for livestock and crops "will increasingly become climatically unsuitable". Extreme agricultural drought over North and South America, Eurasia and the Mediterranean could be up to three times as likely at 2°C of warming. Carbon Brief (2022), *In-depth Q&A: The IPCC's sixth assessment on how climate change impacts the world.*

9 We have conservatively assumed only utility-scale ground-mounted solar is used. The direct land requirements of onshore wind are minimal. The range depends on both the scale of onshore wind and solar PV uptake, and the extent of clean electrification – see ETC (2021), *Making clean electrification possible;* Our World in Data (2022), *Land use of energy sources per unit of electricity;* UNECE (2021), *Lifecycle assessment of electricity generation options;* IEA (2022), *Solar PV tracking report.*

10 Urban areas occupy around 1.5 million km^2. Our World in Data (2019), *Land use.*

11 IEA (2022), *Approximately 100 million households rely on rooftop solar PV by 2030.*

need not exceed the land already dedicated to those resources today, implying no net increase:

- The ETC believes that almost all future bioenergy use could be met from waste and residues, with minimal additional energy crop use. This implies future land use for bioenergy would not go beyond existing levels, which totals 0.5–2.5 million km^2.[12]

- Bioenergy development must still be carefully managed within sustainability limits and used only in applications where alternative zero-carbon technologies are not available.

- Thus, new **additional land use from the energy transition** would only be around 0.4–1.1 million km^2, comparable to the 0.2–0.4 million km^2 used for the fossil fuel energy system.[13]

- However, both energy systems are very small compared with the 51 million km^2 devoted to **agriculture**, of which 41 million km^2 directly (i.e. grazing land) or indirectly (i.e. arable land used for animal feed) supports meat and dairy production. This is a much greater driver of adverse land use impacts, including being the primary driver of deforestation.[14]

- Deforestation is predominantly driven by agriculture,[15] and biodiversity losses are overwhelmingly driven by land-use change for food production, or by climate change impacts induced by use of fossil fuels.[16]

At the global level, there are therefore no significant land resource constraints on the ability to build a massively bigger electricity system based primarily on wind and solar.

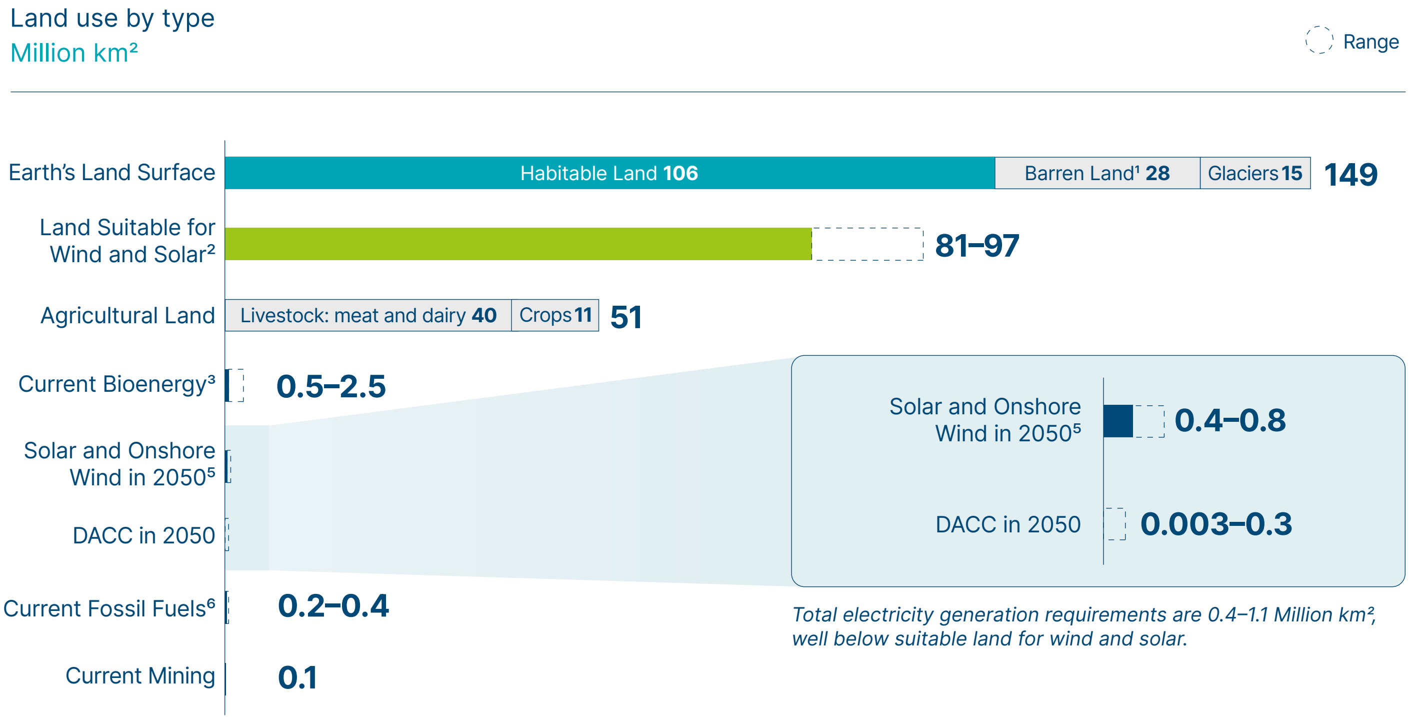
However, in certain countries, constraints across land, wind and solar availability will make it impossible to rely solely (or even primarily) on domestic wind and solar resources to deliver required electricity supply. Conservative estimates of "available" land for wind and solar amount to 0.5–5 million km^2 globally,[17] in excess of the requirements above – but with potential pinch-points at a more local or regional level in resource-constrained or densely poplated countries such as Nigeria or Bangladesh.

In such cases, countries will need to rely either on domestic nuclear power, on the continued use of fossil fuels with carbon capture and storage (CCS), or on the import of zero-carbon power from other countries, whether in the form of electricity (via high-voltage direct current lines), hydrogen, or other energy carriers.

12 The ETC has covered the topic of bioresources extensively in ETC (2021), *Bioresources within a net-zero economy*, including an outline of a sustainable scale of future use of bioresources, alongside the actions required for responsible supply and the trade-offs between different forms of land use, their mitigation potential, and their impacts on nature and biodiversity.
13 Estimated based on Our World in Data (2022), *Land use of energy sources per unit of electricity*; Allred et al. (2015), *Ecosystem services lost to oil and gas in North America.*
14 ETC (2023), *Financing the transition: Supplementary report on the costs of avoiding deforestation.*
15 ETC (2023), *Financing the transition: Supplementary report on the costs of avoiding deforestation.*
16 Jaureguiberry et al. (2022), *The direct drivers of recent global anthropogenic biodiversity loss*; IPBES (2023), *Models of drivers of biodiversity and ecosystem change.*
17 Estimated based on available wind and solar resources and assumptions around availability of land for electricity generation – see Deng et al. (2015), *Quantifying a realistic, worldwide wind and solar electricity supply.*

EXHIBIT 1.2

Land use associated with the energy transition would be over 10x smaller than agriculture, which uses around 50% of global habitable land – but trade-offs might be needed locally



[1] Barren land includes deserts, salt flat, beaches, sand dunes and exposed rocks – see Our World in Data. [2] Suitable land excludes forests, protected areas, land covered in ice, water, cliffs, dunes and rock – see Deng et al. [3] Most future bioresource use of 40–60 EJ p.a. can be met by residues and waste, with energy crops making up only 5–10 EJ. This could be met with land dedicated to existing bioenergy crop production, i.e. 0.5–2.5 million km². [4] Available land accounts for minimum solar and wind resource availability, as well as estimates for the percentage of suitable land that would be available for electricity production – see Deng et al. [5] Includes renewables for green hydrogen production. Assuming only utility-scale ground-mounted solar PV and only accounting for land directly impacted by wind turbines. [6] Estimated from Our World in Data (2022), *Land use of energy sources per unit of electricity*; Allred et al. (2015), *Ecosystem services lost to oil and gas in North America.*

SOURCES: Systemiq analysis for the ETC; Our World in Data (2019), *Land Use*; Deng et al. (2015), *Quantifying a realistic, worldwide wind and solar electricity supply*; ETC (2021), *Bioresources within a net-zero emissions economy*; Our World in Data (2022), *Land use of energy sources per unit of electricity*; UNECE (2021), *Lifecycle assessment of electricity generation options*; Maus et al. (2022), *An update on global mining land use.*

1.1.2 Water requirements for a clean energy system

A clean energy system will have higher water consumption[18] (around 58 billion m³ a year) than a fossil fuel system (around 37 billion m³ a year across power generation and extraction).[19] However, total water consumption will only be equivalent to around 2% of global agricultural water use, which stands at around 2,700 billion m³ each year.[20] Exhibit 1.3 sets out the estimates and comparisons. Key points are:

- **Wind and solar** require no water for operation, but solar panels do require regular cleaning as dust and dirt can prevent sunlight reaching the cells. As an upper limit, water for cleaning solar panels could need up to 4 billion m³ each year – but strong efforts are being made to reduce cleaning requirements.[21]

- **Nuclear** power dominates water requirements for electricity generation and could reach up to 14 billion m³ each year, similar to current fossil fuel power generation needs.[22] As with current thermal power plants, most would be expected to be sited adjacent to rivers or coastal waters.

18 Water consumption is defined as the "net" water used that is permanently lost from a source. This differs from water withdrawal, which is defined as the total amount of water withdrawn from a surface or groundwater source.
19 IEA (2016), *Water-energy nexus.*
20 Our World in Data (2017), *Water use and stress.*
21 1 GW of installed solar capacity requires 45,000–230,000 m³ of water for cleaning each year, but there is ongoing research to reduce water consumption for cleaning. Panat and Varanasi (2022), *Electrostatic dust removal using adsorbed moisture-assisted charge induction for sustainable operation of solar panels.*
22 Assuming maximum nuclear generation of up to 5,700 TWh and water consumption of around 2.5 m³/MWh for nuclear generation, based on Macknick et al. (2012), *Operational water consumption and withdrawal factors for electricity generating technologies.*

- **Green hydrogen** requirements for the electrolysis of water would be at most 11 billion m³ each year.[23]

- **Carbon capture and storage (CCS) and DACC** could require 19–29 billion m³ per annum,[24] This includes water use across point-source CCS, bioenergy with CCS (where bioenergy would predominantly come from waste and residues, as outlined above), and DACC.

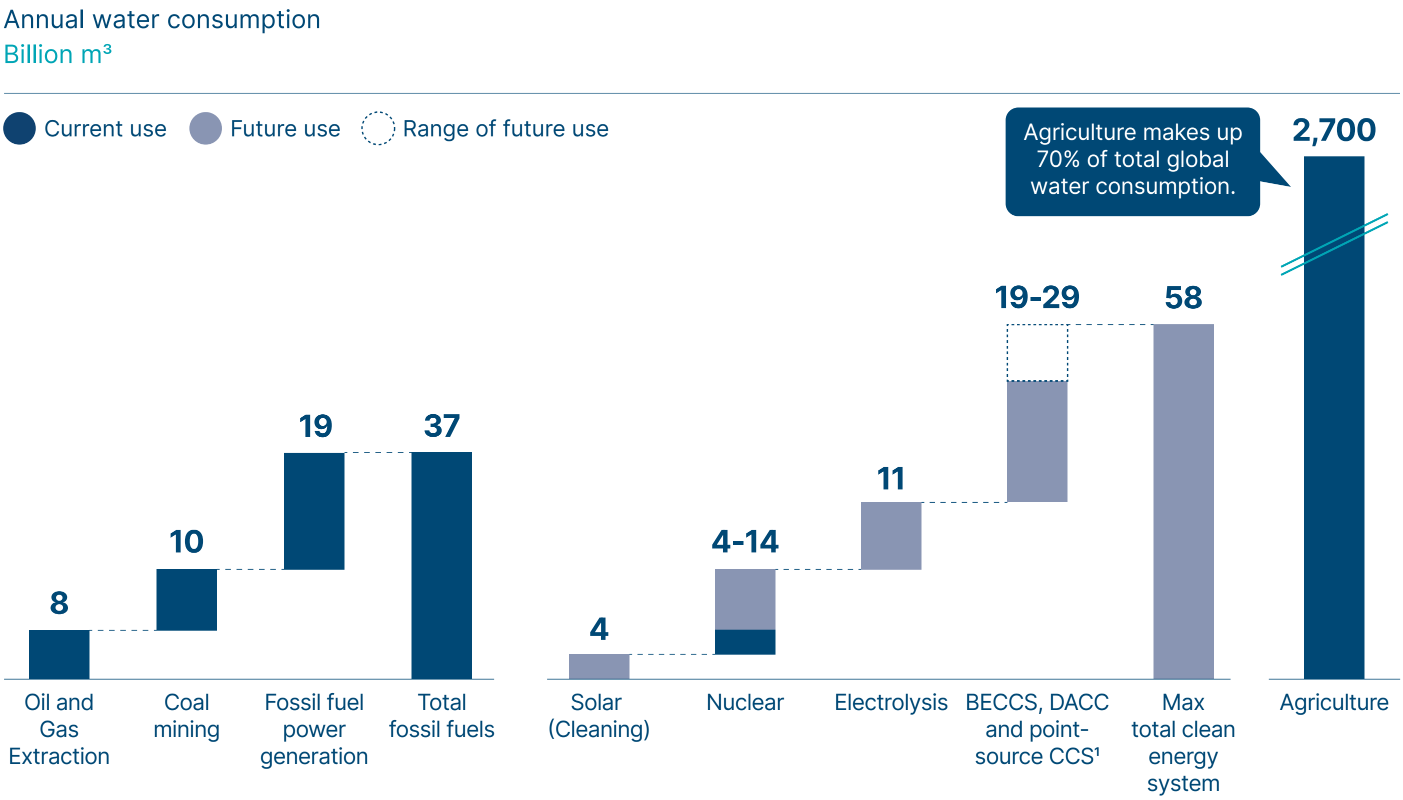
- **Bioenergy production** from energy crops (which the ETC suggests should supply only a small 5–10 EJ of total bioenergy supply) could require water for irrigation, but would be very small relative to total agricultural water use.[25]

Overall, at the global level, water supply is not a constraint on the ability to operate a zero-carbon energy system. In some areas of the world (e.g., deserts or highly water-stressed regions), additional water consumption could create some trade-offs with other demands for water. In areas of the world with abundant saltwater, not freshwater, desalination can be a viable low cost option.[26]

High water consumption for energy transition mining to build a clean energy system (estimated at an additional 4.5 billion m³ per annum at most) could also pose challenges at a local level, requiring careful management.[27] Chapter 4 discusses these challenges and the required response.

EXHIBIT 1.3

Water use for the clean energy system would be higher than for fossil fuels, but well below current agricultural consumption



¹ Does not include water for bioenergy crops, as their use would not be additional beyond today's use of bioenergy. See ETC (2021), *Bioresources within a net-zero emissions economy.*

SOURCES: Systemiq analysis for the ETC; IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*; IEA (2016), *Water-Energy Nexus*; Meissner (2021), *The impact of metal mining on global water stress and regional carrying capacities*; Macknick et al. (2012), *Operational water consumption and withdrawal factors for electricity generating technologies*; Our World in Data (2017), *Water use and stress*; ETC (2021), *Making the hydrogen economy possible*; Smith et al. (2016), *Biophysical and economic limits to negative CO_2 emissions*; Rosa et al. (2021), *The water footprint of carbon capture and storage technologies.*

23 Assuming demand for up to 800 Mt of hydrogen in 2050. ETC (2021), *Making the hydrogen economy possible.*

24 Assuming 2.9–4.8 $GtCO_2$ of point-source CCS at a water intensity of 2 m^3/tCO_2, and 3–4.5 $GtCO_2$ of DACC at a water intensity of 4 m^3/tCO^2, based on ETC (2022), *Carbon capture, utilisation and storage in the energy transition;* Rosa et al. (2021), *Water footprint of carbon capture and storage technologies.*

25 ETC (2021), *Bioresources within a Net-Zero Emissions Economy.*

26 Although energy requirements are quite high (up to 16 kWh/m³), costs for desalination have fallen to below $2/m³, providing an opportunity for expanded use of desalination where local energy, costs, and management of brine discharge permit. Eke et al. (2020), *The global status of desalination: An assessment of current desalination technologies, plants and capacity;* Shokri and Fard (2022), *Techno-economic assessment of water desalination: Future outlooks and challenges.* For example, ICMM members have committed not to explore or mine in World Heritage Sites.

27 It is worth noting that the current fossil fuel system also has significant water consumption associated with mining of metals used in the fossil fuel system (e.g., mining of iron ore for steel).

1.2 Raw material requirements to build a clean energy system

In assessing whether there is sufficient mineral and material supply to support the transition to a clean energy system, it is important to consider both:

- The cumulative demand for new materials needed over the transition – are there sufficient materials available on land? This is discussed in this section.
- The annual demand for new materials versus potential supply – can supply develop fast enough to meet rising demand? This is discussed in Chapter 2.

1.2.1 Material needs for clean energy technologies

Exhibit 1.4 sets out the materials and minerals considered in this report.[28] In some cases, materials such as copper, steel, nickel and aluminium are required across most of the clean energy technologies. And for these materials, demand is also driven by a wide range of other industrial or consumer uses, such as steel for constructing new buildings and copper for electronic products.

In other cases, such as lithium or polysilicon, needs are more specific to certain clean energy technologies (e.g., batteries and solar panels), and the energy transition is the dominant driver of total demand for these materials.

28 Materials not included are, for example: cadmium and tellurium used in thin-film solar PV; iridium used in hydrogen electrolysers; or steel and aluminium used to manufacture electric vehicles – the last is not "additional" energy transition demand, as requirements are similar between internal combustion engine and electric vehicles.
Two materials not included in this study are iridium and tin due to data availability issues:
Iridium is important for the current generation of electrolysers, and demand could rise rapidly to levels in line with existing global supply of 5–8 tonnes per annum. However, high prices and scarce supply are incentivising rapid innovation to reduce the iridium intensity of electrolysers. Kiemel et al. (2021), *Critical materials for water electrolysers at the example of the energy transition in Germany*; Minke et al. (2021), *Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis?*
Tin is used in solder to create electrical connections, for example in electronic circuits. Thus, although not necessarily used directly in clean energy technologies, tin is an important enabling material for the energy transition. Wood Mackenzie (2021), *Tin - the forgotten foot soldier of the energy transition.*

EXHIBIT 1.4

Clean energy technologies will drive increased demand for many key materials

	Solar	Wind	Power Grids	Electric Vehicles and Batteries[1]	Hydrogen Electrolysers	Nuclear	Hydropower	Other Uses
Aluminium	High	High	High	Little/no	Mid	Little/no	Mid	Construction, transport, industry, beverages
Cobalt	Little/no	Little/no	Little/no	High	Little/no	Little/no	Little/no	Consumer electronics, steel alloys
Copper	High	High	High	High	High	Mid	Mid	Industry, construction, electronics, wiring
Graphite (for Anodes)	Little/no	Little/no	Little/no	High	Little/no	Little/no	Little/no	Steel production, lubricants, pencils
Lithium	Little/no	Little/no	Little/no	High	Little/no	Little/no	Little/no	Consumer electronics
Neodymium	Little/no	High	Little/no	High	Little/no	Mid	Little/no	Magnets for industry, consumer electronics
Nickel	Little/no	Mid	Little/no	High	High	Mid	Mid	Steel alloys
Palladium and Platinum	Little/no	Little/no	Little/no	Little/no	High	Little/no	Little/no	Auto catalysts
Polysilicon	High	Little/no	Little/no	Little/no	Little/no	Little/no	Little/no	Alloys, lubricants, semiconductors
Silver	High	Little/no	Little/no	Little/no	Little/no	Little/no	Little/no	Jewellery, industry, investment
Steel	High	High	High	Little/no	High	High	High	Construction, transport, consumer goods
Uranium	Little/no	Little/no	Little/no	Little/no	Little/no	High	Little/no	Defence

Importance of material to clean energy technology:

High | Mid | Little/no requirement, or not applicable

NOTE: [1] Structural steel and aluminium for electric vehicles are not included as energy transition demand, as this is not 'additional' demand – these materials would be used in similar amounts in internal combustion vehicles as well.

1.2.2 Total material requirements to 2050

Total cumulative material requirements for the energy transition are estimated to be around 6.5 billion tonnes of end-use materials, equivalent in mass to less than one year of current coal consumption [Exhibit 1.5]. The basis for these estimates, which allow for the impact of technological innovation and recycling, is described in Chapter 2.[29]

Measured in tonnes of material, demands for steel, aluminium and copper account for 95% of the total end-use material requirements for the energy transition. However, the energy transition's role in driving future demand varies significantly across the three materials:

- In the case of steel, the average annual requirement between 2022–50 of 170 million tonnes would still account for

29 Throughout this report we make use of the mass, in metric tonnes, of materials required on an annual or cumulative basis, as this is the most intuitive and simple way to carry out consistent comparisons. However, we also highlight the variation in rock moved per ton of material in Chapter 4, and the value/market size of different materials in Chapter 3.

less than 10% of today's global steel production of about 1900 Mt per annum. This would correspond to approximately a doubling from current levels of steel demand from the fossil fuel industry of 70–80 Mt each year.[30]

- For aluminium, average annual requirements between 2022–50 could be around 30 million tonnes – around 30% of current annual aluminium production of 110 Mt each year.
- In the case of copper however, the average annual requirement between 2022–50 of about 20 million tonnes compares with today's global annual production for all uses of about 25 million tonnes. Copper demand to support the energy transition therefore implies the need for a big increase in total global copper supply.

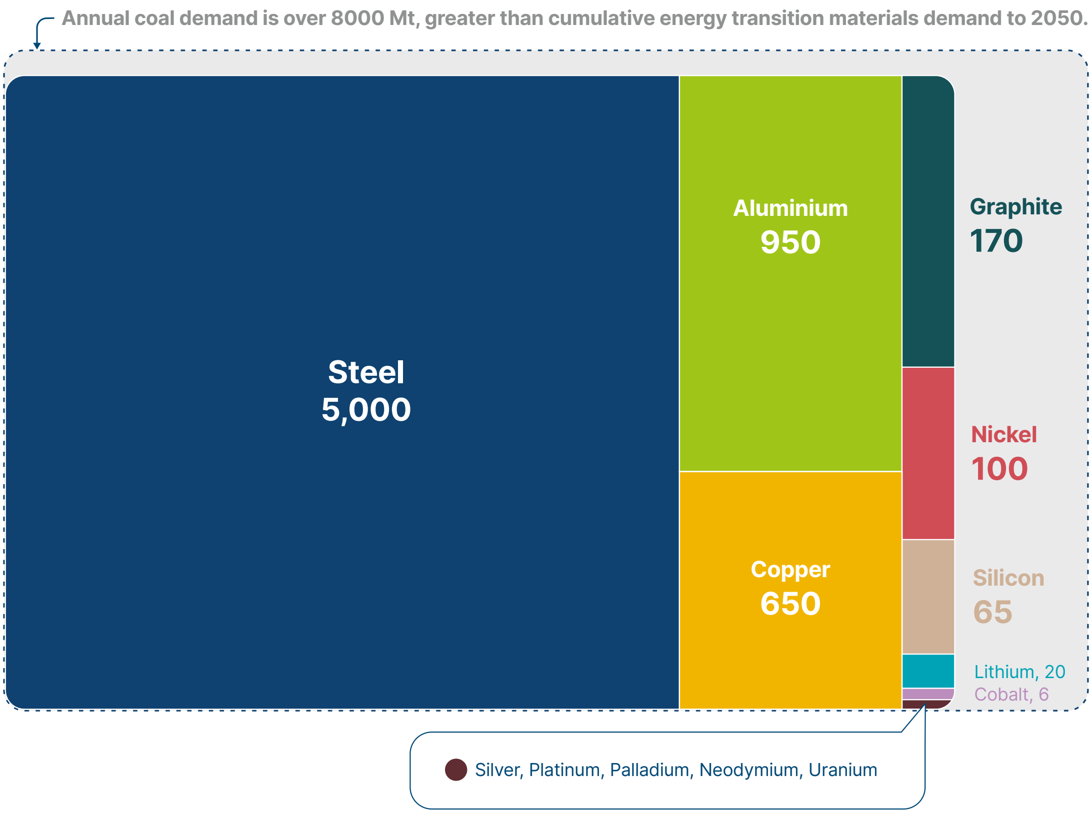
In tonnage terms, demands for some of the most important key materials are trivial. For instance, all the batteries required to power almost total electrification of the world's road vehicles will require at most one million tonnes annually of pure lithium production between now and 2050,[31] with recycling providing the vast majority of any subsequent need.

In value terms however, these minerals are far more relatively important. The current very high market prices for lithium would give a value of $370bn for 1 Mt of pure lithium, whereas 170 Mt of steel might cost around $100bn.[32]

EXHIBIT 1.5

An upper bound of total material requirements for the energy transition would still be less than one year of coal, by mass; steel accounts for over 75%

Cumulative material requirements for the energy transition,[1] 2022–50
Million metric tonnes



NOTE: [1] Based on the ETC's Baseline Decarbonisation scenario, where an aggressive deployment of clean energy technologies leads to global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. This is for end-use of metals/materials, and quantities refer to amounts of contained material. For example, the values given are for end-use aluminium, not mined bauxite, or for elemental lithium, not lithium carbonate/hydroxide.

SOURCE: Systemiq analysis for the ETC; BP (2022), *Statistical review of world energy*.

30 Rystad Energy (2023), *Pedal to the metal – enough material to supply the growth?*
31 For three key battery materials, lithium, cobalt, nickel, amounts discussed in this report are for contained elemental metal, and not for refined products such as lithium carbonate/hydroxide, cobalt sulphate, or nickel sulphate.
32 Using estimated average prices of around $600/ton for steel and $70,000 per tonne of lithium carbonate equivalent (LCE) – or around $370,000 per tonne of contained lithium. Note that 2022 was a year with exceptionally high prices for lithium products. BNEF (2022), *2H Battery metals outlook.*

1.2.3 There are more than enough materials on earth to meet material demands for the energy transition

In assessing the adequacy of material supply to support the energy transition, it is important to understand the meaning of published estimates for resources and reserves [Box A]:

- **"Resources"** are an estimate of material stocks available in sufficient concentration to make exploitation an economic interest at some time. It is important to note that even these estimates tend to increase over time.
- **"Reserves"** are the currently economically and technically extractable subset of resources.

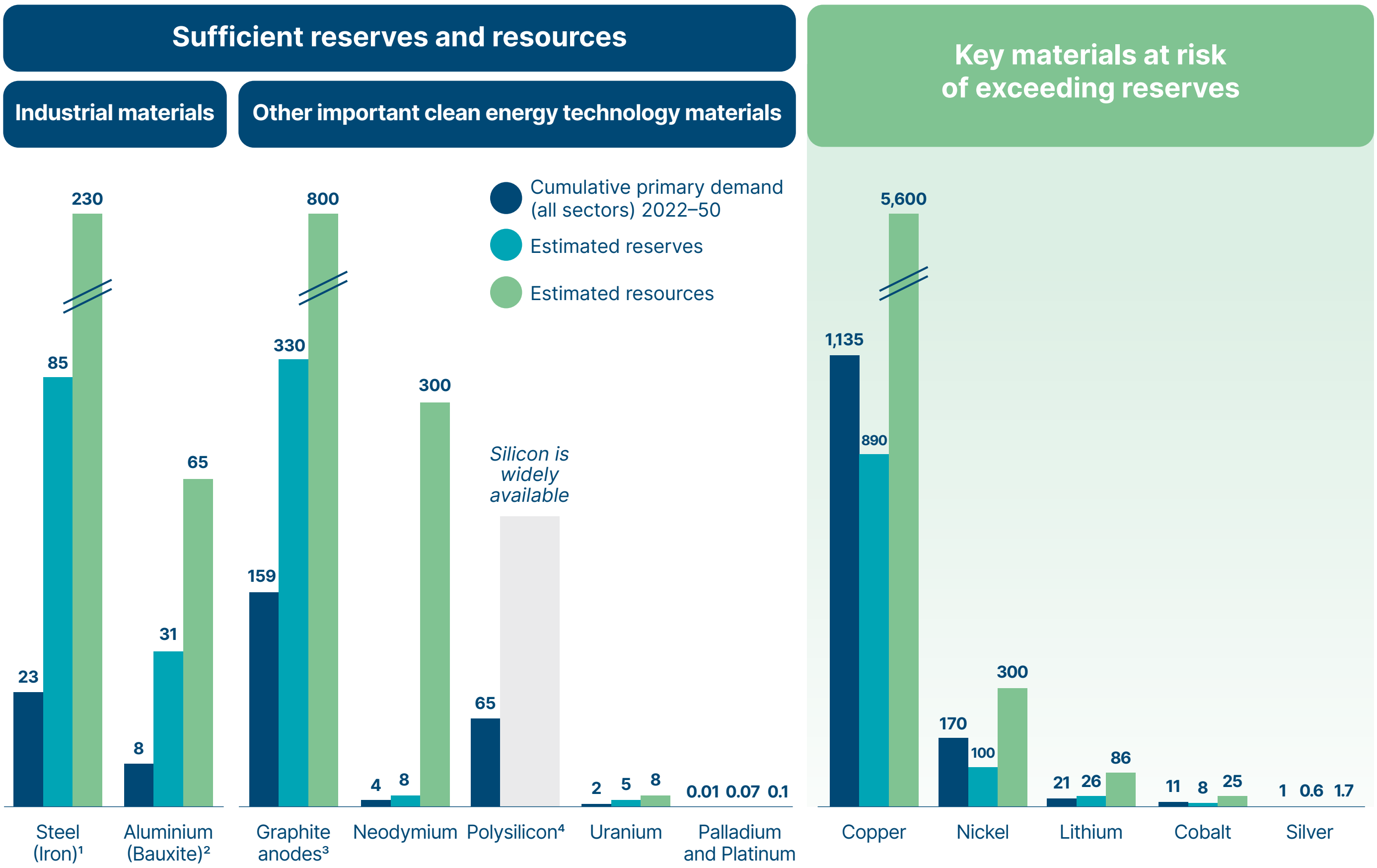
For all the required materials, as Exhibit 1.6 illustrates, currently estimated resources already easily exceed cumulative demand between now and 2050. In most cases, estimated reserves are also in excess of needs.

EXHIBIT 1.6

There are enough resources on land to meet total materials demand between 2022–50, but more exploration to expand reserves will be needed for key energy transition materials

Cumulative primary demand 2022–50 from energy transition and other sectors (Baseline Decarbonisation scenario[5]), compared to estimated reserves and resources

Billion metric tonnes (Industrial materials); Million metric tonnes (All other materials)



[1] Reserves and resources of contained iron. [2] Reserves and resources of bauxite. Demand for aluminium converted to bauxite assuming 4 tonnes of bauxite are required to produce one tonne of aluminium. [3] Graphite reserves/resources refer to natural graphite and do not include synthetic graphite. [4] No estimated reserves for silicon, but quartz (the key input) is widely available in most geographies. [5] Based on the ETC's Baseline Decarbonisation scenario, where an aggressive deployment of clean energy technologies leads to global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns.

NOTE: "Resources" are an estimate of material stocks available in sufficient concentration to make exploitation an economic interest at some time. "Reserves" are the currently economically and technically extractable subset of resources. It is important to note that even these estimates tend to increase over time.

SOURCE: SYSTEMIQ analysis for the ETC; US Geological Survey (2023), *Mineral commodity summaries*.

There is therefore no fundamental shortage of raw materials to support a complete global transition to a net-zero economy, while supporting economic growth powered by greatly increased electricity consumption.

However, for some materials, current estimated reserves are insufficient to meet the levels of demand expected for both the energy transition and other sources of demand. Reserves might need to expand by up to 30% for copper, 70% for nickel, and 90% for silver to meet total expected demand between 2020–50.

Turning resources into reserves is not expected to be a major challenge. A combination of economic incentives, technological developments and increased exploration all tend to lead to expansions in estimated reserves over time [Exhibit 1.8]. However, reserves for some materials are located in sensitive and costly locations, such as tropical regions with high biodiversity, and timelines for developing new mines can take 15 or more years.

Box A: Defining material reserves and resources

Assessment of future material requirements need to consider both current estimates of global resources and reserves of materials [Exhibit 1.7]:[33]

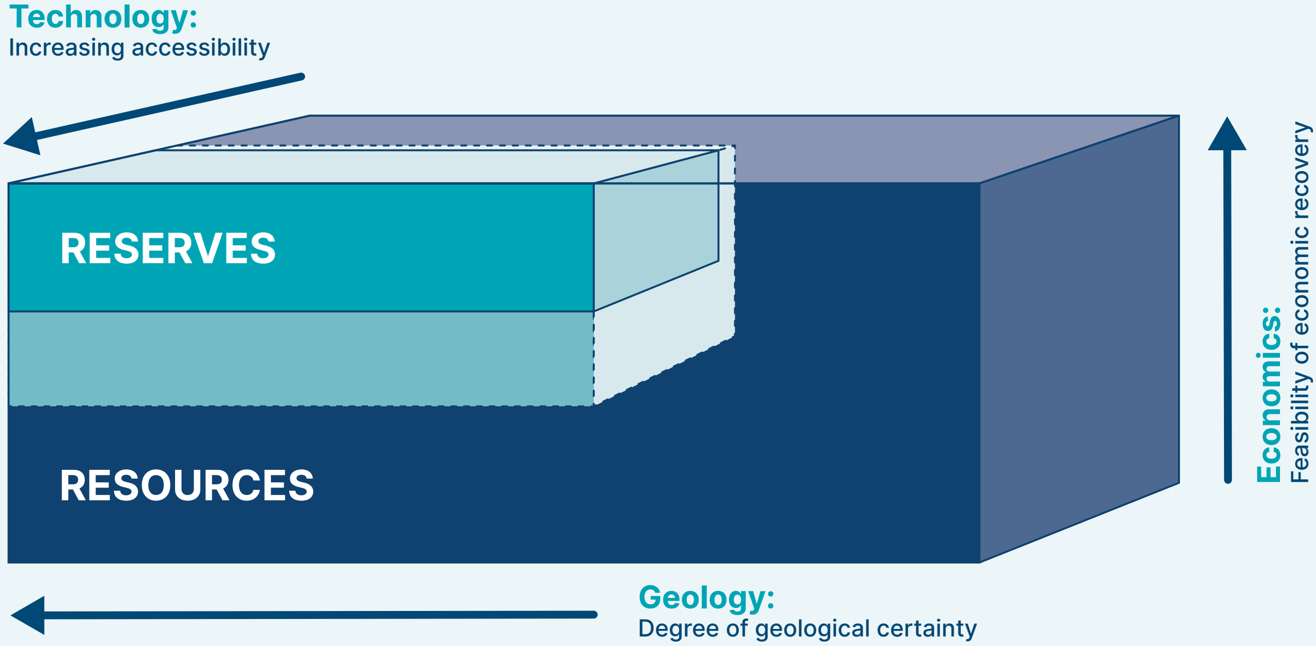
- *Mineral Resources* are natural concentrations of minerals that are, or may become, of potential economic interest. Resources can include inferred, indicated and measured quantities – with increasing level of geological knowledge and confidence.

- *Mineral Reserves* are the currently economically and technically extractable part of resources. Reserves can be sub-divided into probable and proved reserves.

Both resources and reserves are dynamic, and tend to increase over time – even as production depletes existing stocks. Historically, price incentives driving more exploration and improved exploration and extraction technologies have led to an expansion in estimated reserves and resources across most minerals and metals. This can be seen clearly for copper, nickel and lithium in Exhibit 1.8.

EXHIBIT 1.7

Resources and reserves depend on geology, technology and economics



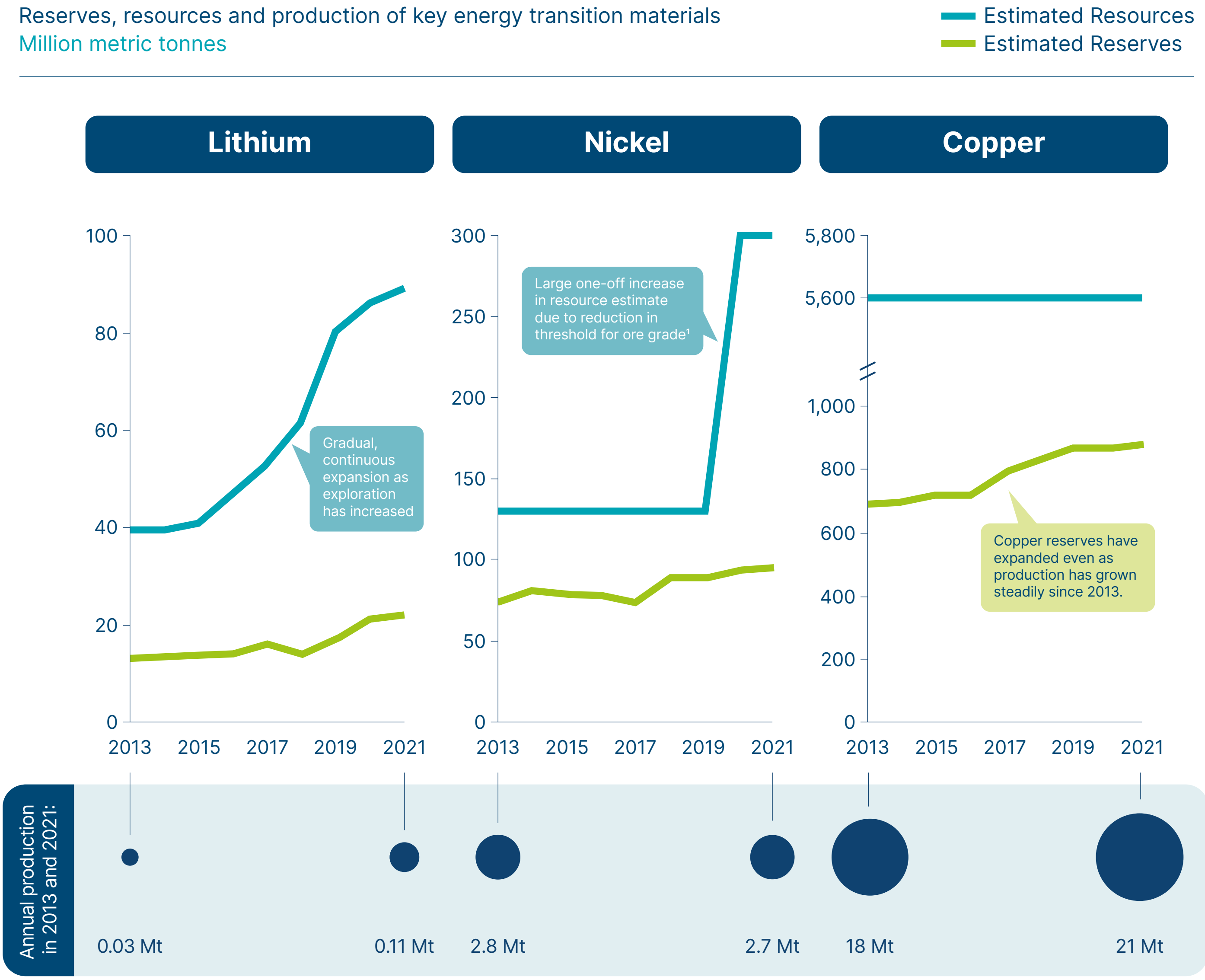
SOURCE: Adapted from British Geological Survey/Minerals UK/NERC (2023), *What is the difference between resources and reserves for aggregates?*

33 Definitions adapted from: British Geological Survey/Minerals UK/NERC (2023), *What is the difference between resources and reserves for aggregates?;* US Geological Survey, *Mineral reserves, resources, resource potential, and certainty;* Boliden (2023), *Mineral resources and mineral reserves.*

EXHIBIT 1.8

Even as production has increased, resources and reserves have expanded, driven by exploration

Reserves, resources and production of key energy transition materials
Million metric tonnes



NOTE: [1] The US Geological Survey reduced the threshold for land-based nickel resources from 1% contained nickel down to 0.5%, increasing the total global estimate of resources.

SOURCE: US Geological Survey.

1.3 The new system vs. the old – a dramatically reduced impact on the global environment

Building, operating and maintaining a low-carbon energy system will have a significant impact on some local environments. It is impossible for over nine billion people to enjoy a good standard of living without the need to extract large resources and without some adverse environmental impacts at a local level.

However, it is important to understand that:

- A clean energy system will have the single biggest impact on limiting global warming and avoiding the environmental impacts of climate change. These avoided impacts are dramatically larger than the environmental impacts associated with a clean energy system.
- The local environmental impacts associated with material and resource extraction for a clean energy system may be of the same order of magnitude as for a fossil fuel based system, but these will likely be largely one-off; in comparison, the impacts of maintaining a fossil fuel energy system would occur in perpetuity.

1.3.1 Global emissions and climate impacts

Building a zero-carbon economy will in itself result in some CO_2 emissions. The first generation of wind turbines, solar panels, or batteries, have to be made using fossil fuel based energy, and the first generation of electric vehicles will use electricity from grids which have not yet been fully decarbonised.

It is therefore important to identify the total life cycle emissions involved in low carbon technologies and how those life cycle emissions will change over time. Details of this analysis are set out in Chapter 4 and suggest that, over the whole period 2022–50, extracting and producing the materials needed for clean energy system may result in about 35 $GtCO_2e$ of cumulative emissions.

But this **cumulative** 35 $GtCO_2e$ compares with the 41 $GtCO_2e$ emissions produced by the current **fossil fuel-based energy system every year** – and would likely be even lower (see Chapter 4, Section 4.1).[34] Furthermore, if we remained with a fossil fuel-based energy system, those 41 $GtCO_2$ emissions a year would continue in perpetuity, and potentially grow.

In comparison, life-cycle emissions for clean energy technologies are already lower than their fossil-based alternatives [Exhibit 1.9], and the stock of emissions entailed in building a net-zero energy system will be one-off – once the electricity system is decarbonised, building the wind turbines, solar panels and batteries required to support further economic growth will be produced with zero-carbon energy and will have near-zero life cycle emissions.[35]

It is important to assess the life cycle emissions arising from all the activities involved in building a net-zero economy as accurately as possible and to reduce them as fast as possible. However, it is vital to recognise that building a net-zero economy, with all its material needs, is the only way to reach net-zero emissions and to limit harmful climate change.

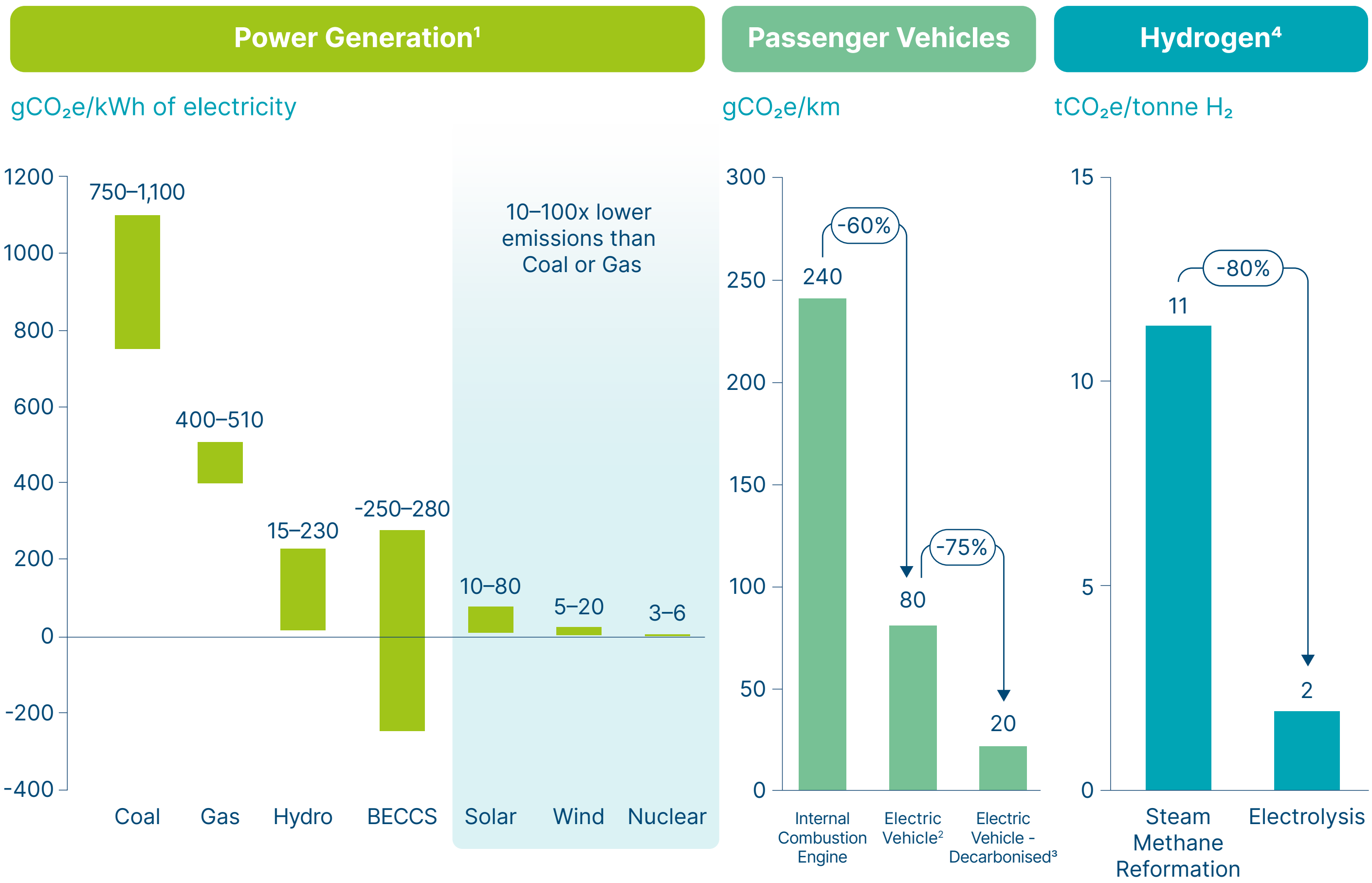
34 IEA (2023), *CO_2 emissions in 2022*. The value of 41 $GtCO_2e$ includes emissions from industrial processes and waste, and assumes a GWP100 value of 30 for methane – see Exhibit 4.1.

35 It is important to note that by 2050 there will still be a small, but residual role for fossil fuels. By 2050, the total scale of fossil fuels in a net-zero aligned system could be at most 650 million tonnes of coal (including both thermal coal for fossil fuels and metallurgical coal for steel production), and 3.2 billion tonnes of oil and gas (the scale of sustainable biomass use for energy would remain similar to current levels of 40–60 EJ per annum in 2050). This will be to support energy system balancing in some countries (e.g., where the seasonal intermittency of renewables is an issue), and because some parts of the world will be slower to transition to a clean power system (e.g., those heavily endowed or economically depend on fossil fuels). This is based on 2050 demand of 1,400–3,000 bcm of gas and 10–20 Mb/d of oil. The ETC will be covering this topic in detail in an upcoming report on fossil fuels. Source: Systemiq analysis for the ETC, based on ETC (2020), *Making mission possible;* ETC (2022), *Mind the gap;* IEA (2021), *Net zero by 2050: A roadmap for the global energy sector;* BP (2023), *Energy Outlook – Net zero scenario;* Shell (2021), *Energy transformation scenarios – Sky scenario;* BNEF (2022), *New energy outlook – Net Zero Scenario.*

EXHIBIT 1.9

All clean energy technologies have significantly lower associated emissions than their fossil-fuel counterparts

Life-cycle emissions of fossil fuel vs. clean energy technologies



NOTES: [1] Includes upstream emissions of methane from coal and gas production. Emissions from BECCS include those from land use change, operation and carbon capture and storage, see Pehl et al. [2] For a medium-sized vehicle purchased in 2022, with a battery made in China and charged using the EU's average grid intensity. [3] For a medium-sized vehicle purchased in 2030, with a battery made in Sweden and charged using solar power. Remaining emissions are from manufacturing of the vehicle and battery, and upstream emissions in electricity generation. [4] Assuming low-carbon power is used for electrolysis (carbon intensity of 37 gCO_2e/kWh), and including methane leakage during production via steam methane reformation. Residual emissions for electrolysis are from electricity supply.

SOURCE: Pehl et al. (2017), *Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling;* UNECE (2021), *Integrated life-cycle assessment of electricity sources*; Transport & Environment (2022), *How clean are electric cars – online tool*; IEA (2023), *Energy technology perspectives.*

These avoided emissions mean that a clean energy system will result in a dramatic reduction in future environmental and human impacts, compared to continuing the current fossil fuel system. The IPCC has covered such impacts extensively, and these avoided climate change impacts include:[36]

- **Water scarcity**: at 2°C of global warming, 3 billion people could face water scarcity, rising to 4 billion at 4°C. Extreme agricultural drought is projected to be twice as likely at 1.5°C, and 150-200% more likely at 2°C.
- **Biodiversity and nature:** at 2°C of global warming, roughly one-in-ten species are likely to face a very high risk of extinction – and this share rises to 12% at 3°C.
- **Human health and wellbeing:** Extreme heat is a major risk, alongside increased spread of diseases (especially mosquito-borne ones). The IPCC estimates that an additional 250,000 deaths each year from "climate-sensitive diseases and conditions" could be attributable to climate change.[37] Further, the rapid increase in urbanisation across Asia and Africa could expose hundreds of millions more people to heat and flooding extremes.

36 IPCC (2022), *Climate change 2022: impacts, adaptation and vulnerability;* Carbon Brief (2022), *Explainer: Can climate change and biodiversity loss be tackled together.*
37 Compared to the 1961–91 baseline average, and for mid-emission scenarios. IPCC (2022), *Climate change 2022: Impacts, adaptation and vulnerability.*

1.3.2 Local environmental and human health impacts

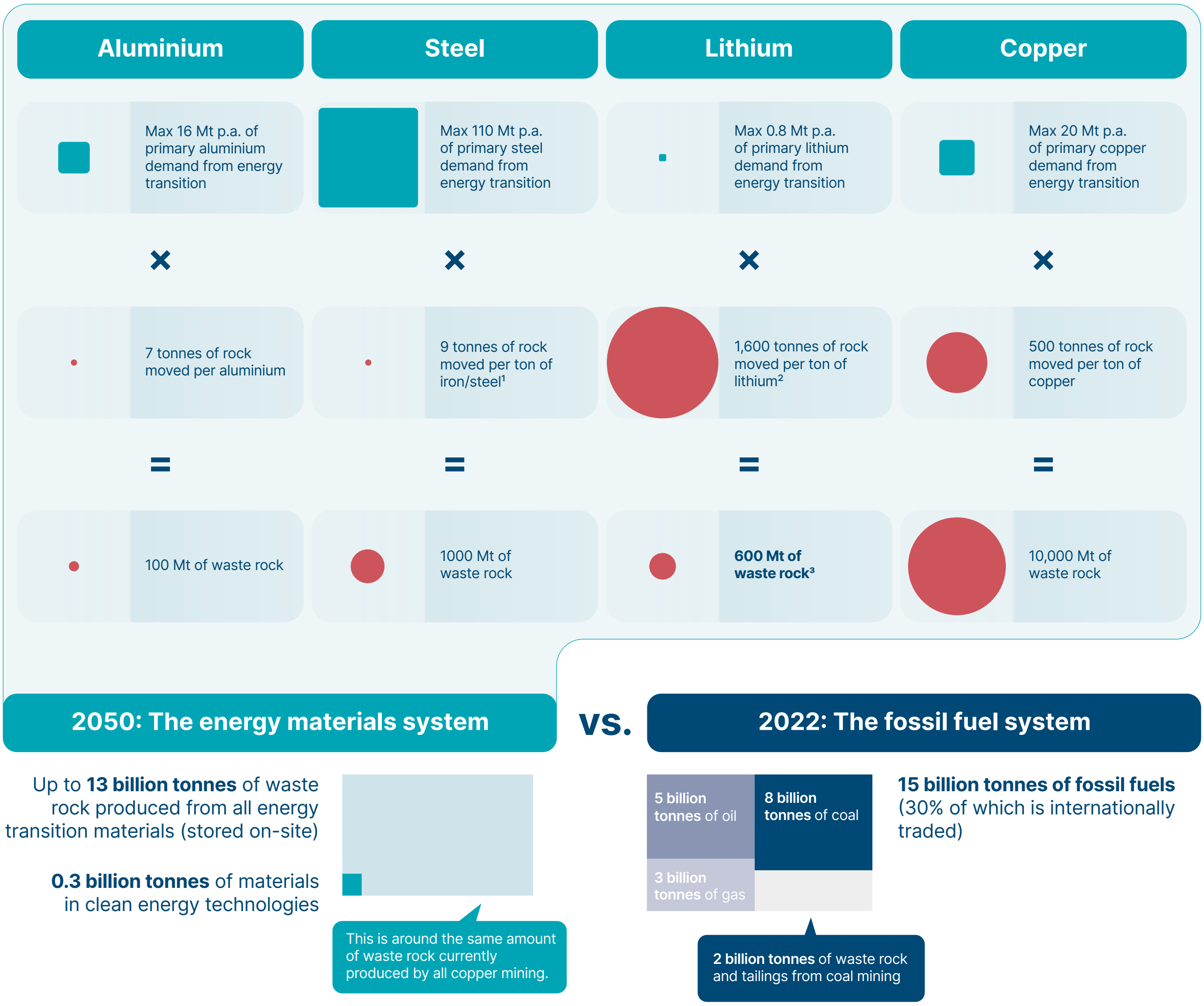
The extraction of the raw materials required to build a net-zero economy may have significant environmental impacts in some locations, including pollution relating to effluents discharge and leakage from tailings. Chapter 4 sets out these potential impacts in detail and describes how these can be better identified, managed and reduced.

Exhibit 1.10 illustrates the key example of waste rock produced by different types of materials – an issue determined by ore grades, a key factor in associated environmental impacts of particular materials.

EXHIBIT 1.10

Energy transition demand for materials could lead to up to 13bn tonnes of waste rock each year – less than the 15bn tonnes of fossil fuels extracted and burned each year

Annual waste rock moved to produce materials for the energy transition



NOTE: Waste rock accounts for both ore grade and for additional waste rock moved (e.g. overburden). Material requirements are based on the ETC's Baseline Decarbonisation scenario, where an aggressive deployment of clean energy technologies leads to global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The 13 billion tonnes total includes all materials assessed in this report. [1] Steel tends to have >95% iron content, so mass of steel required is assumed to be equivalent to mass of iron required. [2] For lithium mined from hard rock. [3] Assuming lithium from hard rock makes up half of total lithium supply.

SOURCE: Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes*. IEA (2023), *CO_2 emissions in 2022*; IEA (2022), *Coal 2022*; IEA (2022), *Oil market report – December*; IEA (2022), *Gas market report, Q4*; ICMM (2022), *Tailings reduction roadmap*.

During the transition, these local environmental impacts could be on the same order of magnitude as maintaining the current fossil fuel based system, although they will differ in severity and nature in specific locations (see Chapter 4 for a detailed discussion). This is because while a clean energy system requires at most around 0.3 billion tonnes of materials each year, extracting them requires moving up to 13 billion tonnes of waste rock [Exhibit 1.10] – an amount roughly similar to the current global copper system.38 However, two points should be kept in mind:

- The current fossil fuel system relies on the extraction of 15 billion tonnes of coal, oil and gas[39] – together with 2 billion tonnes of waste rock and tailings from coal mining.[40]
- Of these, around 4 billion tonnes are internationally traded over thousands of kilometres[41] – whereas waste rock and tailings from mining are typically moved at most a few kilometres within a mine site.

Further, there will be a clear environmental benefit of a reduction in air pollution from avoided combustion of fossil fuels:

- Mining and combustion of fossil fuels leads to the emission of nitrogen oxides and fine particulate matter that results in illness and millions of premature deaths each year, predominantly driven by coal mining and coal-fired power generation.[42] Combustion of bioenergy also leads to emissions of nitrogen oxides and particulate matter, though overall volumes of bioenergy combustion will be significantly smaller than fossil fuel combustion today.
- Life cycle analyses show that wind, solar and nuclear electricity generation has an impact on human deaths that is 1000x lower than coal and 100x lower than gas.[43]
- In the case of electric vehicles, the significant weight of batteries means that non-exhaust emissions (mainly from brake, tyre and road wear) from the driving of vehicles will still remain even as the road transport fleet is electrified.[44] However, the scale of this issue is much smaller than the impacts on human health from combustion of fossil fuels.

In addition, the key point is that today's energy system, based on the continuous extraction and consumption of fossil fuels would lead to these environmental impacts occurring **every year in perpetuity**.

In comparison, the material extraction required to build a clean energy system will be, to a large extent, one-off. The materials extracted will be deployed in durable technologies which, over the long-term will be significantly recycled, as explained in Chapter 2. This means that mining needs for the energy transition will greatly reduce in coming years.

1.4 Summary

Analysis of global cumulative resource requirements shows that there are no fundamental long-term barriers to building a zero-carbon energy system, which can support widespread global prosperity in a sustainable way. However, there may need to be short-term trade-offs and open discussions around land use or water consumption in particularly resource-constrained countries or regions.

Over the long-term, any trade-offs across land use, water consumption or material requirements for a clean energy system are more than manageable when compared to the existing fossil fuel or agricultural systems [Exhibit 1.11] – as well as reducing emissions to avoid climate change and its associated impacts on resources and the environment.

The key issues are therefore not the long-term feasibility or desirability of a clean energy system, but:

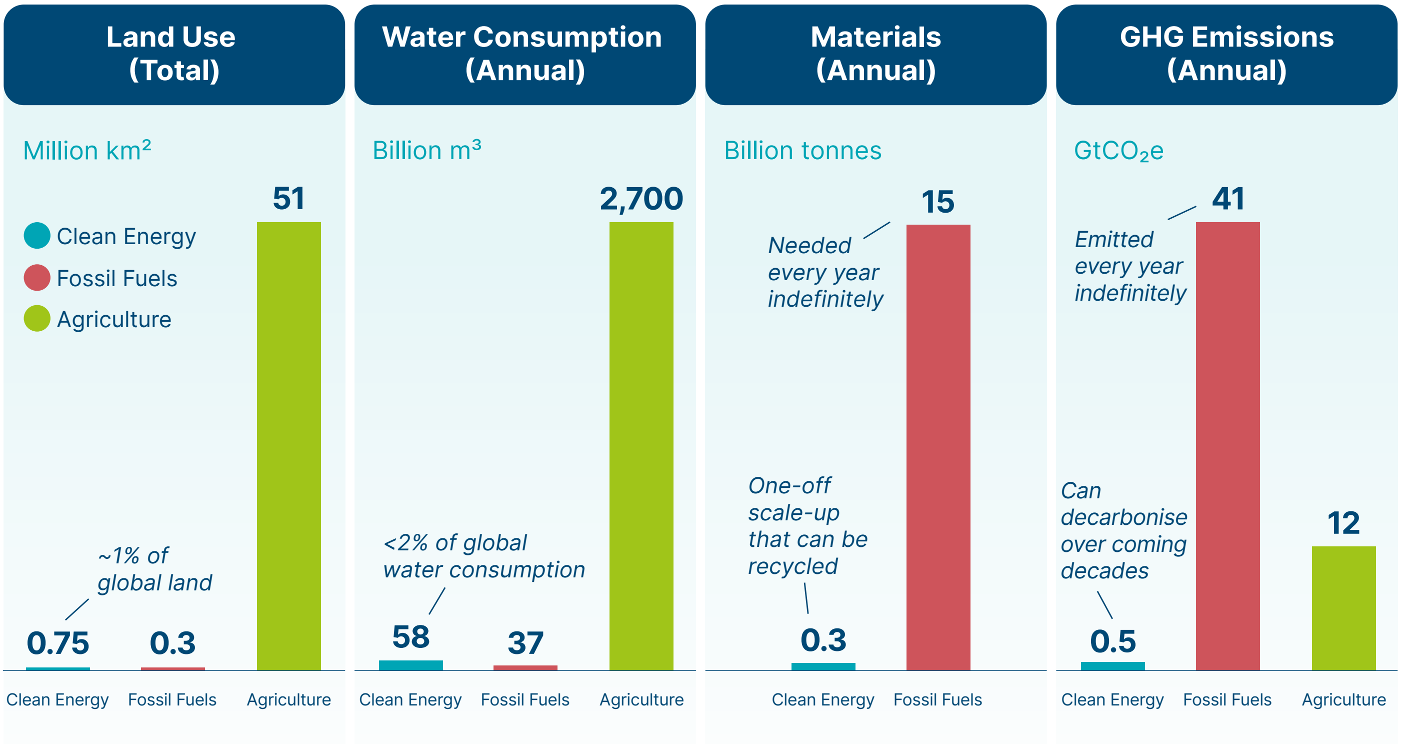
- The challenge of ramping up materials supply fast enough to decarbonise the global economy at the pace required. This is considered in Chapters 2 and 3.
- The challenge of ensuring mining for key materials occurs in a sustainable and responsible way which manages and minimises local environment impacts. This is considered in Chapter 4.

38 Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes.*
39 IEA (2022), *Coal 2022;* IEA (2022), *Oil market report – December;* IEA (2022), *Gas market report, Q4.*
40 ICMM (2022), *Tailings reduction roadmap.*
41 BP (2022), *Statistical review of world energy.*
42 There is a range of estimates of global deaths attributable to fossil fuel particulate emissions, see e.g., McDuffie et al. (2021), *Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales*, which estimates approximately 1.1 million premature deaths annually, or Vohra et al. (2021), *Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem,* which estimates around 8.7 million premature deaths annually.
43 Our World in Data (2022), *What are the safest and cleanest sources of energy?*
44 OECD (2020), *Non-exhaust particulate emissions from road transport;* Harrison et al. (2021), *Non-exhaust vehicle emissions of particulate matter and VOC from road traffic: A review.*

EXHIBIT 1.11

A clean energy system will have manageable land, water and material needs, and drastically lower emissions

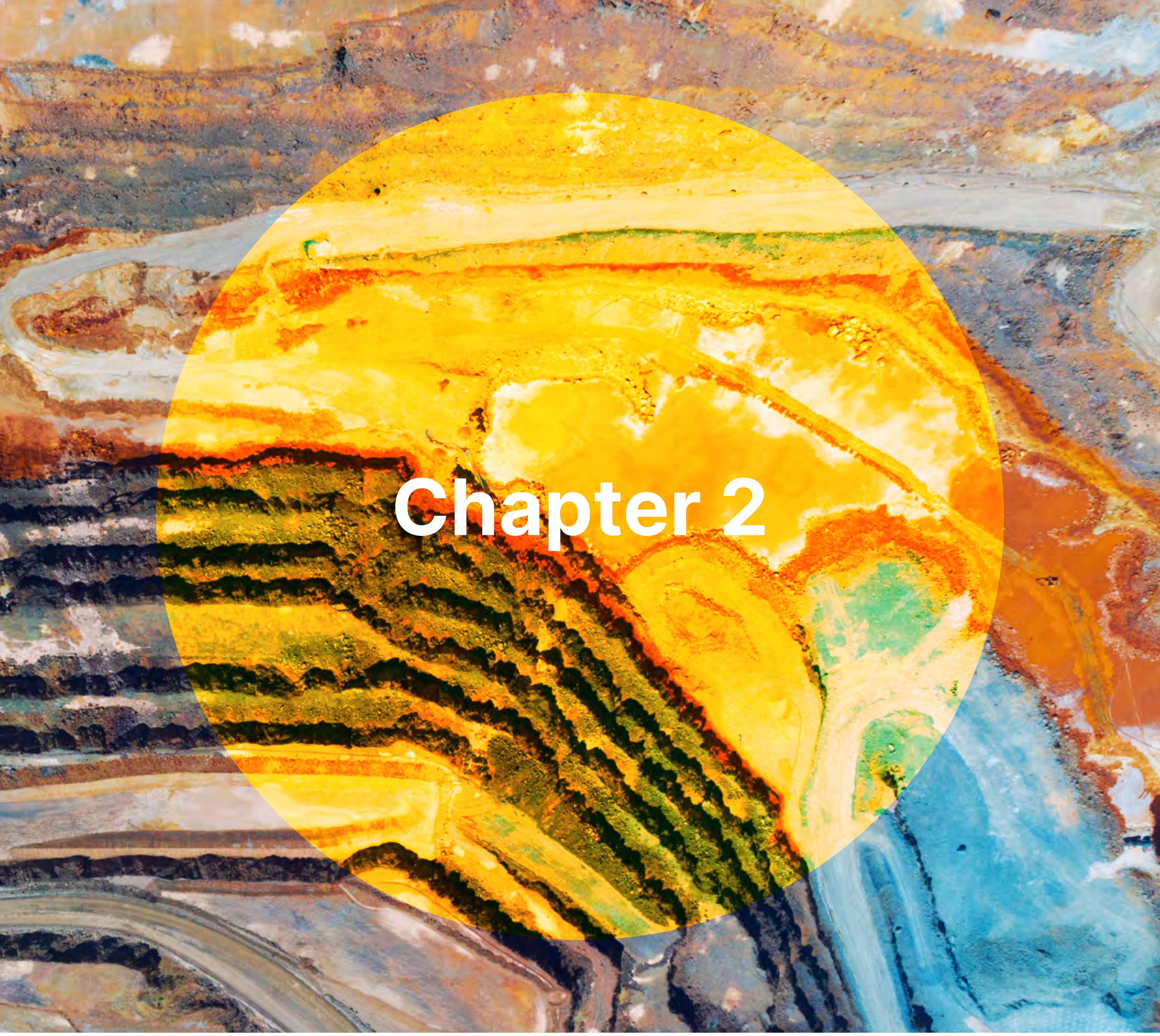
Energy and Agriculture, Resource Requirements and GHG Emissions



Key Assumptions:

	Land Use (Total)	Water Consumption (Annual)	Materials (Annual)	GHG Emissions (Annual)
Clean Energy	Land use for electricity generation in 2050 (not bioenergy), including for green hydrogen and DAC, assuming ground-mounted utility-scale solar and only direct land use for wind.	Water consumption in 2050 for cleaning solar panels, nuclear power, hydrogen electrolysis, and CCS.	Maximum additional material needs to build clean energy technologies in 2050, including e.g. steel for wind turbines, lithium in batteries, copper in cabling.	Maximum potential emissions associated with production of materials for clean energy technologies, assuming current emissions intensities.
Fossil Fuels	Estimated current land use for coal mining and oil and gas extraction.	Current water consumption for coal mining, oil and gas extraction, and fossil power generation.	Current annual extraction of coal, oil and gas used in energy system.	Current emissions associated with fossil fuels and energy system.
Agri-culture	Current land use for agriculture including crops and livestock for meat and dairy.	Current water consumption for all agriculture.	Not applicable here – but global agricultural crop production in 2021 was ~9.5 billion tonnes.	Current emissions associated with agriculture and land-use change.

SOURCE: Systemiq analysis for the ETC; Our World in Data (2019), *Land Use; IEA, Water-Energy Nexus* (2016); Our World in Data (2017), *Water use and stress*; Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes.* IEA (2023), *CO_2 emissions in 2022*; IEA (2022), *Coal 2022*; IEA (2022), *Oil market report – December*; IEA (2022), *Gas market report, Q4*; UN FAOSTAT (2023), *Crops and livestock products*; IEA (2023), *Scope 1 and 2 GHG emissions from oil and gas operations in the Net Zero Scenario, 2021 and 2030*; IEA (2023), *CO_2 Emissions in 2022*; UNEP (2022), *Emissions gap report 2022.*



Supply-demand balance to 2030 and the potential for efficiency and recycling

Current supply pipelines do not appear sufficient to meet rapidly growing demand from the energy transition, with supply gaps and high prices possible for six key energy transition materials (cobalt, copper, graphite, lithium, neodymium and nickel). There is major potential to reduce future demand for energy transition materials via technology and materials efficiency and recycling. These can help reduce cumulative primary materials requirements from the energy transition, and potentially close supply gaps through to 2030. Action to accelerate both materials efficiency and recycling should be strongly supported and required by public policy – especially for battery materials and copper.

Chapter 1 considered the big picture of whether there are enough resources available to meet the raw material demands for the energy transition over the long-term. In this chapter, we set out the details of our demand scenarios, and assess how potential demand growth to 2030 compares with estimates of planned supply. This chapter is also accompanied by Material Factsheets, covering key information for six key energy transition materials (cobalt, copper, graphite, lithium, neodymium and nickel).

We cover in turn:

1. The structure of our demand model – four scenarios for decarbonisation and materials demand.
2. Baseline demand growth for metals for the energy transition, relative to planned supply – specific challenges in the 2020s.
3. The potential to reduce demand and required supply through technical innovation and recycling.
4. Remaining reserve and supply gaps.
5. Policy action to drive technical innovation and recycling.

2.1 Materials demand projections for the energy transition – four scenarios

Chapter 1 began by describing the key technological and investment drivers of the energy transition, with clean electrification at the core. The starting point for our demand model is a set of assumptions which translate this into demand for raw materials. This requires making assumptions about:

- Technical efficiency factors, such as GW of power capacity per GWh of generation.
- Product design factors, such as kWh per EV battery.
- Material intensity factors, such as kg of material per kW or per kWh.

The key driving assumptions for our scenarios are shown in Exhibit 2.1. These are the fundamental drivers of materials demand, in line with and derived from the ETC's broader body of work, and are designed to ramp up aggressively – achieving rapid, deep decarbonisation to reach net-zero emissions by mid-century – and apply across all four scenarios in this report.[45]

45 Deployment of clean energy technologies is designed to be consistent with previous ETC work on the energy transition. See ETC (2020), *Making Mission Possible;* ETC (2021), *Making Clean Electrification Possible;* ETC (2021), *Making the Hydrogen Economy Possible;* ETC (2022), *CCUS in the energy transition: vital but limited.*

EXHIBIT 2.1

ETC assumptions for clean energy technology deployment to 2050

Energy

Technology	Year	Projection	Technology	Year	Projection
Solar Power Generation	2022	1,600 TWh	**Stationary Storage**	2022	0.1 TWh
	2030	6,500 TWh		2030	2 TWh
	2040	20,000 TWh		2040	5 TWh
	2050	40,700 TWh		2050	11 TWh
Wind Power Generation	2022	2,100 TWh	**Green Hydrogen Production by Electrolysis**	2022	<1 Mt
	2030	7,900 TWh		2030	20 Mt
	2040	25,000 TWh		2040	290 Mt
	2050	50,000 TWh		2050	700 Mt
Nuclear Power Generation	2022	2,800 TWh	**Hydrogen Fuel Cells** (Energy demand from aviation and shipping)	2022	1 TWh
	2030	3,500 TWh		2030	75 TWh
	2040	4,900 TWh		2040	1000 TWh
	2050	4,600 TWh		2050	2700 TWh
Transmission and Distribution Grid (Total Direct Electrification)	2022	28,000 TWh	**DACC/CCS**	2022	0.05 $GtCO_2$
	2030	35,000 TWh		2030	1 $GtCO_2$
	2040	56,000 TWh		2040	5 $GtCO_2$
	2050	78,000 TWh		2050	10 $GtCO_2$

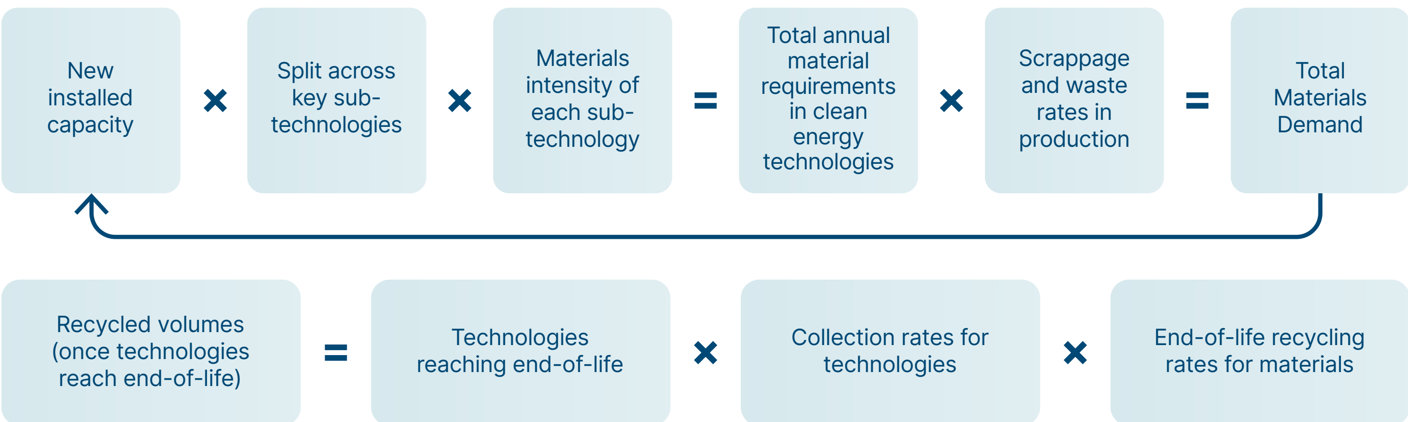
Transport

Technology	Year	Projection	Technology	Year	Projection – light	Projection – mid/heavy
Passenger Electric Vehicle Sales	2022	10 million	**Commercial Electric Vehicle Sales** (Light vs. Mid/Heavy)	2022	0.3 million	0.03 million
	2030	88 million		2030	6 million	1 million
	2040	97 million		2040	16 million	4.5 million
	2050	98 million		2050	17.5 million	9 million
Passenger Electric Vehicle Fleet	2022	60 million	**Commercial Electric Vehicle Fleet** (Light vs. Mid/Heavy)	2022	1 million	0.05 million
	2030	450 million		2030	28 million	4.5 million
	2040	1.3 billion		2040	150 million	35 million
	2050	1.5 billion		2050	270 million	100 million

These driving assumptions are combined with a range of inputs across technology and materials efficiency, and waste management and recycling at end of life, to calculate material flows [Exhibit 2.2].

EXHIBIT 2.2

Illustrative calculation of material requirements



We then vary the assumptions to generate four scenarios:

- A **Baseline Decarbonisation** scenario which ramps up the deployment of the different technologies to achieve a mid-century net-zero economy in line with the ETC's vision, alongside relatively conservative "business-as-usual" assumptions on technology efficiency and innovation, materials intensity, and recycling. Given the very rapid deployment of clean energy technologies, outputs can be seen as an "upper bound" for material requirements for the energy transition.

- A **High Efficiency and Innovation** scenario with more optimistic assumptions on technical efficiency, material intensity and a pivot to less material-intensive technologies (e.g., higher solar and wind capacity factors, smaller battery requirements for EVs, reduced or changed material inputs per kW of solar or wind capacity, or per kWh of battery).

- A **High Recycling** scenario with more intense process scrap and end-of-life recycling, which in some specific minerals achieves recycling rates of over 90% by 2050 and increases so-called "secondary supply".

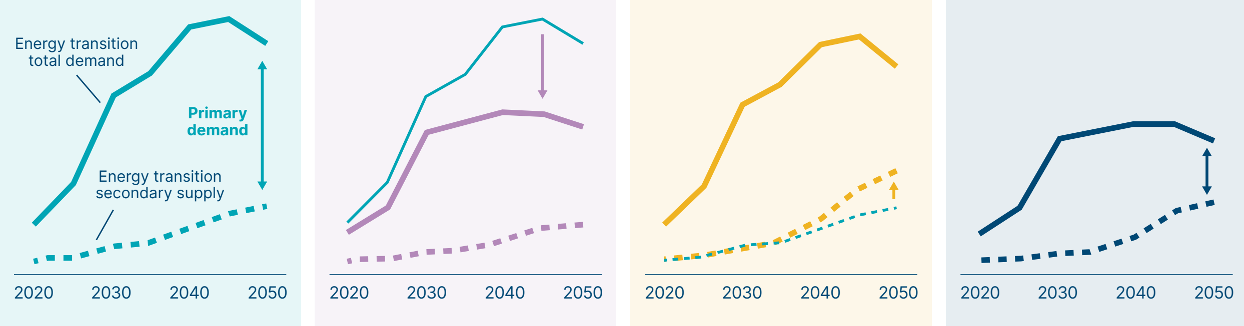
- A **Maximum Efficiency and Recycling** scenario which combines progress on both technical efficiency and innovation and recycling.

For each of the scenarios, we produce estimates of potential annual demand from the energy transition in 2030, 2040 and 2050, based on both total materials demand and secondary supply of recycled materials [Exhibit 2.3].[46]

EXHIBIT 2.3

Four ETC scenarios explore the impact that efficiency and recycling can have on total material requirements and the secondary supply of materials for the energy transition

	Baseline Decarbonisation	High Efficiency and Innovation	High Recycling	Maximum Efficiency and Recycling
Aligned to Net-zero by 2050	✓	✓	✓	✓
Max reduction in total material demand	✗	✓	✗	✓
Max increase in secondary supply	✗	✗	✓	✓
	Maximum demand pathway for a material, based on uptake of clean energy technologies.	Lower, slower ramp-up in demand due to reduced material requirements. Smaller secondary supply due to lower through-flow of materials.	Improved waste management, recycling, reuse - secondary supply increases.	Lower material requirements and increased recycling. Demand for primary supply of materials is much lower.



46 We also make use of external forecasts for non-energy transition demand through to 2050, and for primary and secondary supply of materials through to 2030. These are detailed for each material in Exhibits 2.4 and 2.15.

In Chapter 1, we compared cumulative demand under the Baseline Decarbonisation scenario with current resources and reserves to illustrate that there is no fundamental long-term problem of resource adequacy, even under assumptions that yield the highest material requirements.

In this Chapter, we compare demand scenarios out to 2030 with estimates of planned supply over that period.

2.2 Balance of demand versus supply to 2030 in the Baseline Decarbonisation scenario

Exhibit 2.4 shows demand projections in the Baseline Decarbonisation scenario together with initial projections of potential supply, including both primary mined supply and secondary recycled supply.[47]

Some key features of the demand picture are:

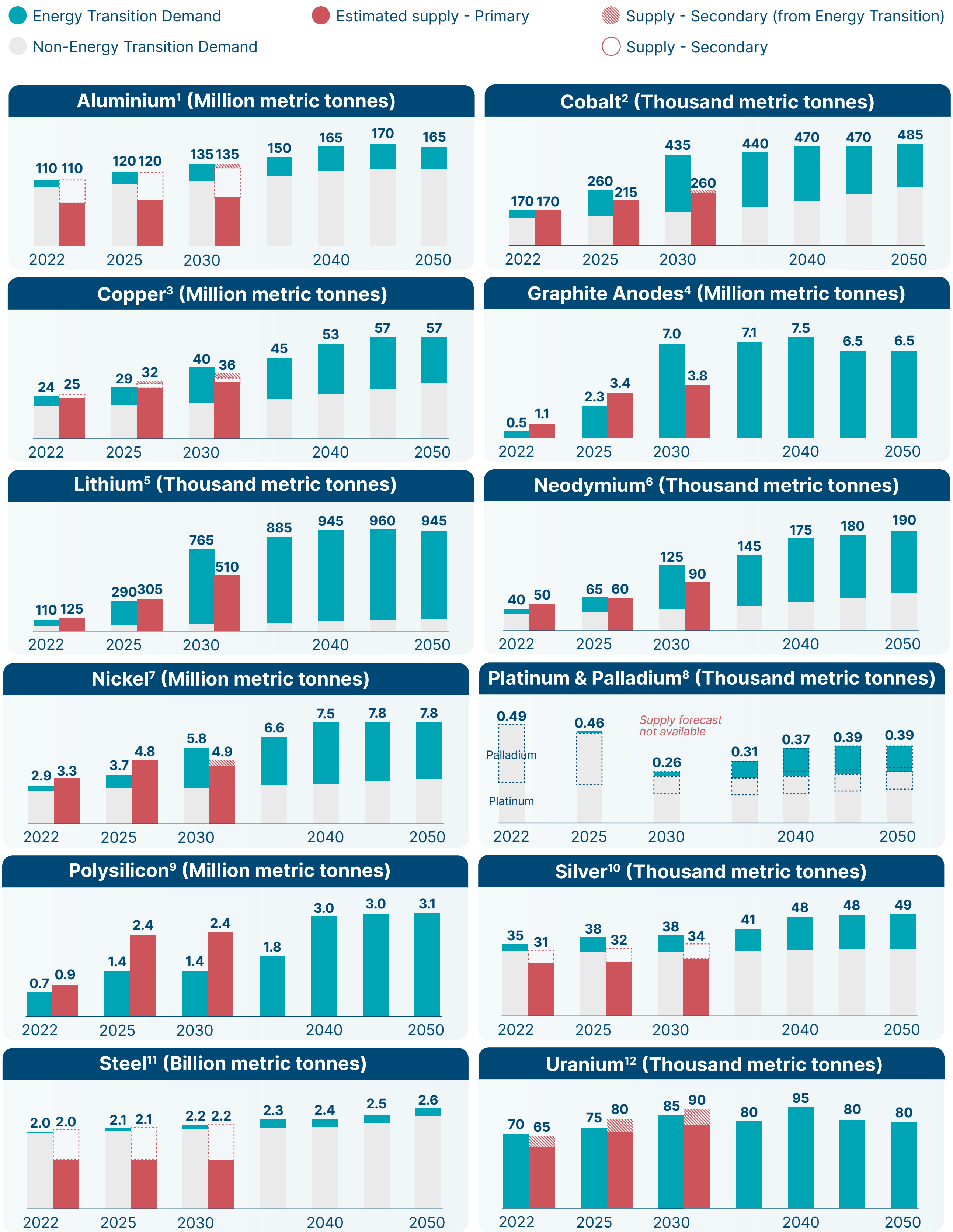
- Volumes of steel and aluminium grow significantly, but primarily because of growth in non-energy related demands (e.g., with greater urbanisation and industrialisation driving demand for steel in lower-income countries).
- Copper, nickel and cobalt demand growth reflects both energy transition and non-energy related factors.
- Energy transition driven demand for lithium, graphite and cobalt increases considerably to 2030, but flattens out thereafter as EV penetration reaches high levels.

For many of the materials in the second and third categories, where the energy transition drives strong demand, demand growth to 2030 is well beyond historical precedent in recent years.[48]

47 Secondary supply estimates are also external, and ETC calculations of secondary supply from clean energy technologies at end-of-life is added on to total supply estimates.
48 One plausible comparator is the growth in steel demand during the commodity supercycle of the early 2000s, where production of iron ore rose from 970 Mt in 2000 up to 1,870 Mt in 2010, as prices nearly quadrupled over the same period. USGS (2020), *Iron ore statistics*; McKinsey & Co. (2022), *The raw-materials challenge*.

EXHIBIT 2.4

Baseline Decarbonisation: Annual material demand and supply



SOURCE: [1]Non-energy demand and secondary supply from Mission Possible Partnership/International Aluminium Institute, primary supply from BNEF (2023), *Transition metals outlook*; [2]Non-energy demand from IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, supply from BNEF (2022), *2H Battery Metals Outlook*; [3]Non-energy demand from BNEF (2022), *Global Copper Outlook*, primary supply from BNEF (2023), *Transition metals outlook*, secondary supply from non-energy transition is assumed to be 10% of primary supply; [4]Supply from BNEF (2022), *2H Battery Metals Outlook*; [5]Same as [2]; [6]Non-energy demand from IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, supply estimated assuming CAGR in REO production from 2010-21 continues to 2030, with neodymium making up 17% total supply; [7]Non-energy demand and supply from BNEF (2023), *Transition metals outlook*; [8]Non-energy demand modelled from phase-out of ICE cars, adding other sector demand, following BNEF (2021) *2H Hydrogen Market Outlook*; [9]Supply from BNEF (2023), *1Q Global PV Market Outlook*; [10]Non-energy demand and supply from Silver Institute (2022), *World Silver Survey*, extrapolated to 2050/30; [11]Non-energy demand and primary/secondary supply from Mission Possible Partnership; [12]Supply from World Nuclear Association (2021), *The Nuclear Fuel Report: Expanded Summary.*

Comparing the Baseline Decarbonisation scenario with planned supply suggests that:

- Steel and aluminium supply will grow broadly in line with increased demand to 2030, with a large and growing percentage of the supply of both coming from "secondary" (i.e., recycled material) – reflecting high existing end-of-life recycling rates for both materials.[49]

- Recycling is also important for copper, but recycled supply from clean energy technologies plays a minimal role before 2030, as with other key battery materials (graphite, lithium, cobalt, nickel), since very few EVs will have reached end of life by then.

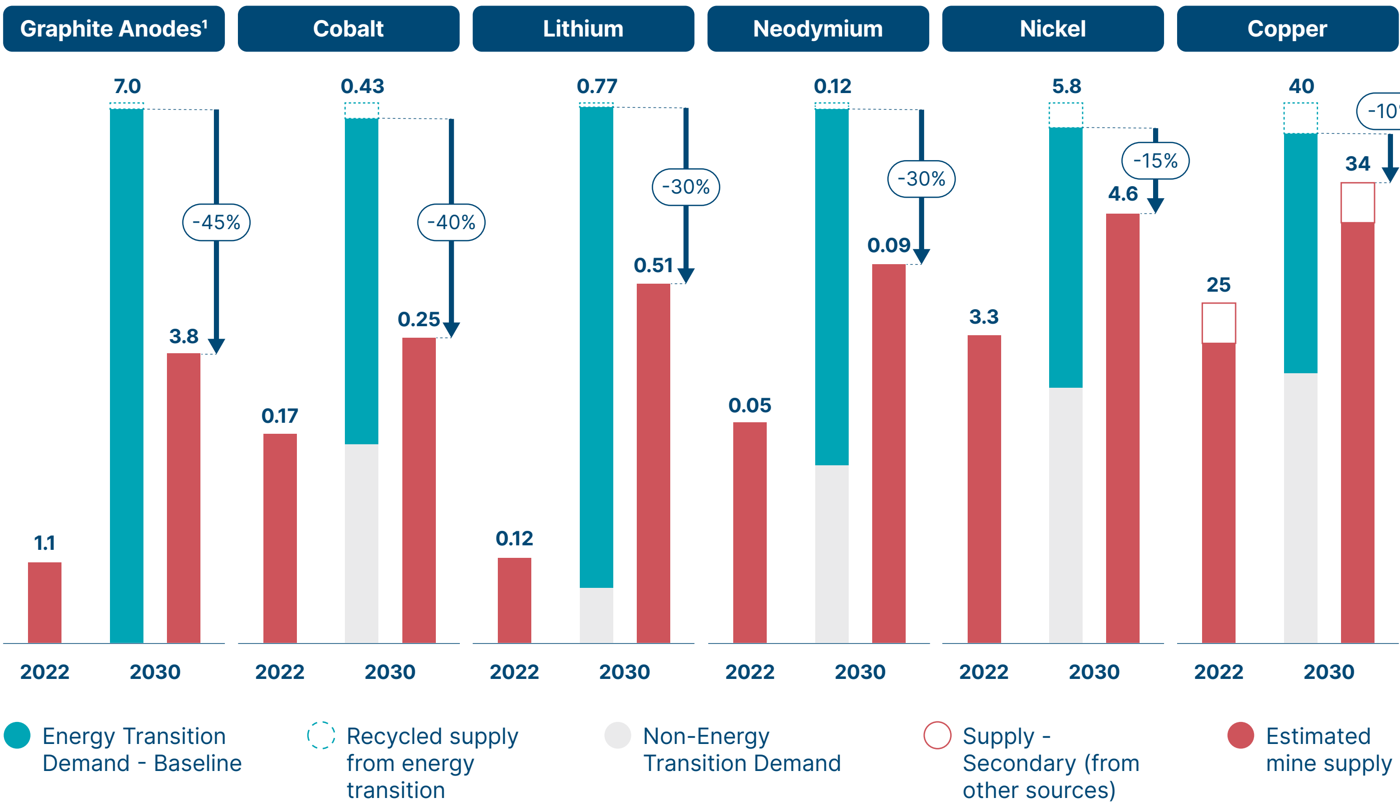
- Although planned supply for many materials is expanding, it still falls short of demand in six key materials – copper, graphite, lithium, nickel, cobalt and neodymium which are highlighted as the energy transition materials at greatest risk in Exhibit 2.5.[50]

There will also be demand for specific chemicals driven by the deployment of CCS, both for industrial point sources and for direct air carbon capture. This is discussed in Box B.

EXHIBIT 2.5

The short-term challenge: Estimated supply growth for key materials is insufficient to meet rapidly rising demand by 2030

Annual demand and supply in 2030 (Baseline Decarbonisation scenario)
Million metric tonnes



NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. [1]Supply only shown for natural graphite – it is likely that synthetic graphite could close most of the remaining supply gap.

SOURCE FOR ENERGY TRANSITION DEMAND: SYSTEMIQ analysis for the ETC.

SOURCE FOR NON-ENERGY TRANSITION DEMAND: Copper – BNEF (2022), *Global copper outlook*; Nickel – BNEF (2023), *Transition metals outlook*, Lithium, Cobalt, Neodymium – IEA (2021), *The role of critical minerals in clean energy transitions.*

SOURCE FOR PRIMARY SUPPLY: Copper, Nickel – BNEF (2023), *Transition metals outlook*, and assuming recycled copper from non-energy transition sources is 10% of primary supply; Graphite Anodes, Lithium, Cobalt – BNEF (2022), *2H Battery metals outlook*; Neodymium – estimated assuming continued CAGR in rare earth oxide production from 2010–21, through to 2030, with neodymium making up 17% of total supply.

49 Current end-of-life recycling rates for steel and aluminium are around 75% and 70%. Fraunhofer ISI (2022), *A dynamic material flow model for the European steel cycle,* and MPP (2022), *Making Net-Zero Steel/Aluminium Possible.*

50 We do not include silver in this group of materials of concern given the very high share of non-energy transition demand for silver, from which demand-shifting is possible, alongside potential to increase secondary supply.

BOX B: Demand for chemicals from carbon capture and storage

The ETC has identified the use of CCUS in the energy transition as vital, but limited. At most 7–10 GtCO_2 of carbon capture could be required by 2050, across a wide range of applications including industrial point source CCS, BECCS and DACC [Exhibit 2.6, LHS].[51]

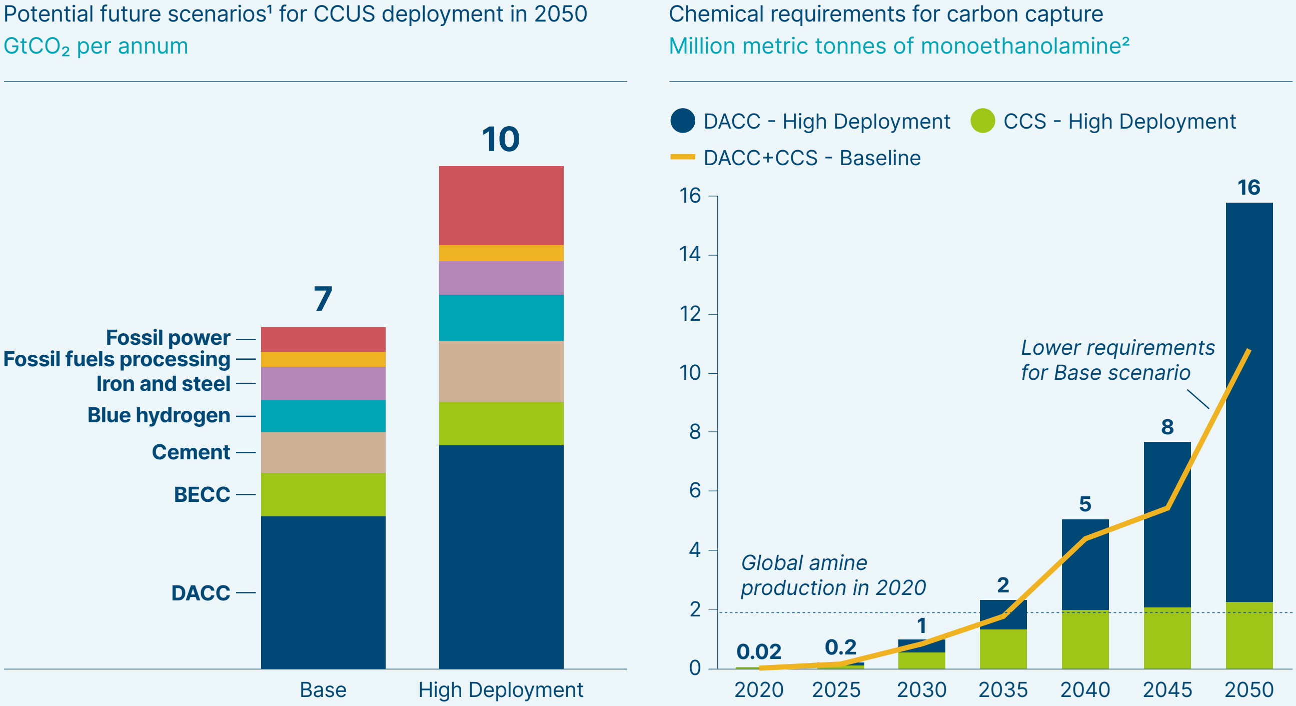
Both CCS and DACC make use of chemical sorbents/solvents that bind to carbon dioxide, to remove them from the air or a stream of gases. Cycles of cooling and heating in the capture process lead to some degradation of the solvents, meaning that a fairly constant throughput of solvents is required for every tonne of CO_2 that is captured.

We have estimated chemicals requirements in the form of monoethanolamine, but in reality, a range of chemicals could be used. These are typical petrochemicals produced from hydrocarbons, but production using alternative feedstocks to fossil fuels should be feasible in coming decades (and there could be a shift to alternative solid-sorbent or membrane-based technologies).

The scale-up in chemicals requirements would be fast and significant, exceeding current global annual production by the mid-2030s [Exhibit 2.6, RHS]. However, overall requirements by 2050 would correspond to an eight-fold increase from current production levels – not unprecedented increase in the history of chemicals, e.g. volumes of nitrogen fertiliser production increased more than five-fold between 1960–80.[52]

EXHIBIT 2.6

The scale-up of solvent production required for DACC and CCS is well within historical precedents for the chemicals industry



¹ The two scenarios are designed to show the plausible range of CCUS requirements in 2050, depending on the evolution of technologies and costs over time. The "Base" scenario is aligned with previous ETC pathways that predominantly involved supply-side decarbonisation of the energy system – see ETC (2020), *Making mission possible*; ETC (2022), *Carbon capture, utilization & storage in the energy transition.*

² Monoethanolamine is a chemical sorbent that is typically used for carbon capture, and is used here as a proxy for total demand across all sorbents.

SOURCE: Systemiq analysis for the ETC; ETC (2022), *Carbon capture, utilization & storage in the energy transition*; RMI and Third Derivative (2022), *Direct air capture and the energy transition.*

51 ETC (2022), *CCUS in the energy transition: Vital but limited.*
52 Rocky Mountain Institute (2022), *Direct air capture and the energy transition.*

2.3 The potential for efficiency and recycling

Pressure on the primary supply of materials can be significantly reduced over the long-term by increasing efficiency and reducing total material requirements, and by increasing recycling and thus the share of demand which is met by secondary supply. The impacts of these actions would become evident over different time horizons:

- Over the short term, actions to improve materials and technology efficiency have the strongest impact on reducing material demand, helping to close supply gaps to 2030, with potential greatest in battery materials.
- Over the mid-to-long term, shifting to next-generation technologies and scaling recycling can together significantly reduce primary material requirements, leading to falling primary demand from the mid-2030s onwards.
- Secondary supply will play a major role in meeting demand from the late-2030s onwards for key materials such as cobalt, graphite and lithium.

Exhibit 2.7 sets out the technological trends and actions which will make it possible to reduce primary material demand via both the technical innovation and recycling levers.

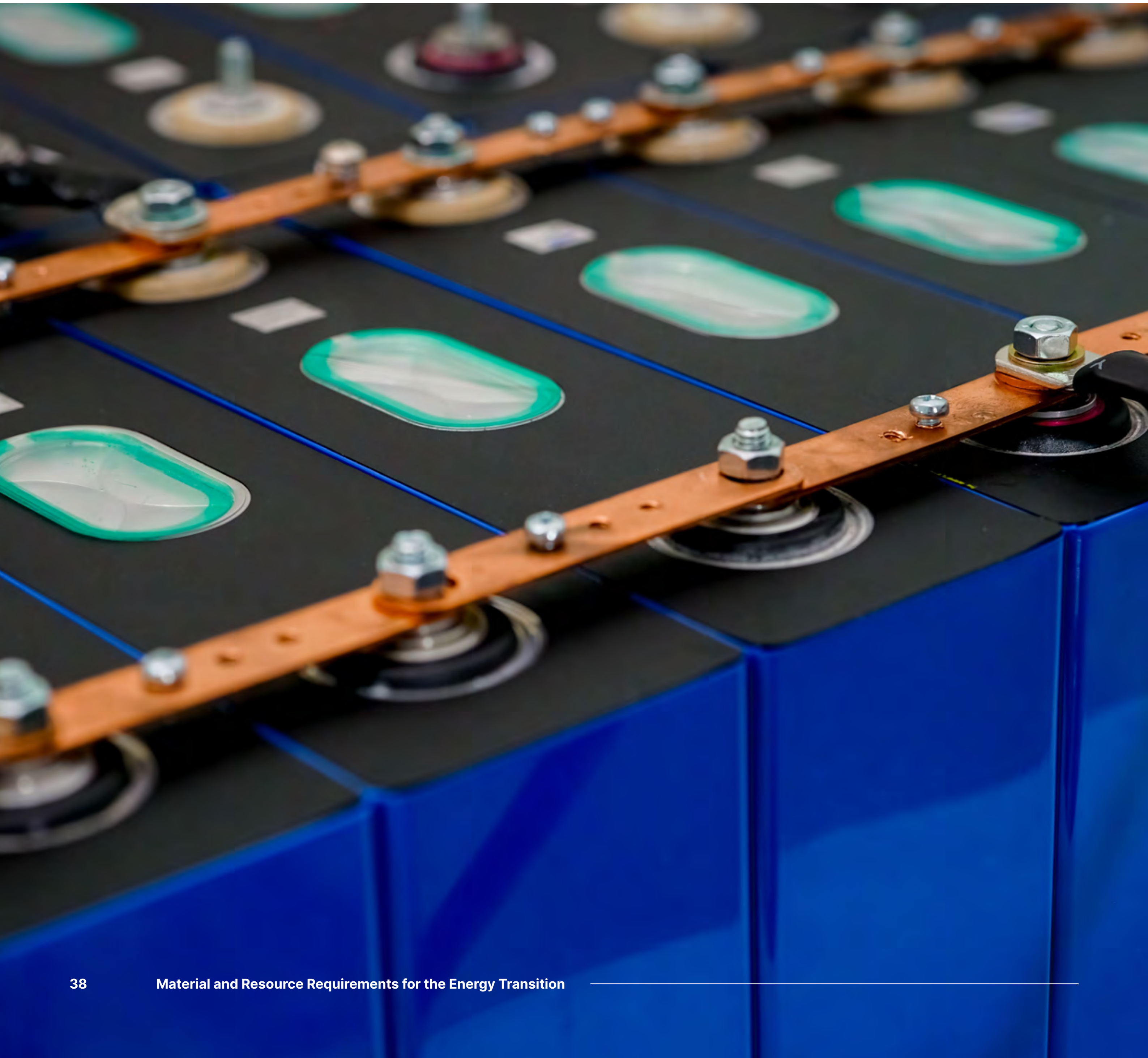


EXHIBIT 2.7

Technology trends and actions to drive innovation, efficiency and recycling

	Technology and Materials Efficiency	Recycling and Waste Management
Solar	1 Optimal siting, reduced inverter losses, slower degradation, drives capacity average factors up to 17% by 2050.[1] 2 Operating lifetimes for solar farms go up to and beyond 35 years. 3 Faster reductions in materials intensity, especially for silicon, aluminium and silver (in module) and copper (on site), driven by efficiency rising to 30% by 2050.[1]	1 By 2040/50, over 70/90% of solar panels are collected for recycling at end-of-life. 2 Initially, this could require incentives such as higher charges on landfill, subsidies for recycling, or higher payments for recovery of particular materials to help scale recycling as it is not currently economical.[2]
Wind	1 Increasing size of turbines, greater use of floating offshore, help drive higher capacity factors: up to 50/55% by 2050 for on/offshore wind.[3] This in turn drives a lower materials intensity per TWh of electricity generated. 2 Operating lifetimes for wind farms go up to and beyond 35 years. 3 If supply constraints are severe, a shift away from permanent-magnet based turbine designs can reduce requirements for rare earth elements.	1 By 2040/50, over 70/90% of wind turbines are collected for recycling at end-of-life. 2 Currently almost all the body of a wind turbine, which is predominantly steel, can be recycled; the challenge is recycling blades made of complex fibres and composite materials. 3 Funding for continued research, development and deployment will be crucial to enabling recycling of composite materials.[4]
Power Grids	1 Connection of VRE plants directly to distribution network uses lower-voltage cabling, which has lower materials needs than higher-voltage. 2 Power flow routing, dynamic line-rating, digitalisation, smart demand management and other measures can increase efficiency and reduce redundancy in grid operation, reducing required grid build-out.[5] 3 Slowing down shift towards underground cabling can help; underground cables are much more materials-intensive than overground.[6]	1 Increasing collection of copper from redundant or end-of-life cabling etc. – rates are assumed to reach 80/90% by 2040/50. 2 Replacing older, inefficient cabling can both unlock old stocks of copper that can be recycled and increase the efficiency of the grid.
Batteries and Electric Vehicles	1 Improved design and packing can help increase battery energy density, making vehicles lighter and improving range.[7] 2 Shift away from SUV sales can help limit size of batteries in passenger and commercial vehicles – e.g. average passenger vehicle has a battery of ~55 kWh through to 2050. 3 A faster shift to lithium iron phosphate (LFP) batteries can reduce requirements for nickel and cobalt; over long term (post-2030) sodium-ion batteries can reduce dependence on lithium. 4 Increased doping of graphite anodes with silicon can reduce need for natural or synthetic graphite. 5 Improved design, efficiency and integration of EV motors and battery can reduce copper, rare earth content.	1 By 2040/50 over 80/90% of batteries are collected for re-use or recycling at end-of-life. 2 By 2040/50 over 25/30% of EV batteries are re-used in stationary storage applications. 3 Reducing EV battery capacity degradation: max ~15% fall after operation, leaving sufficient capacity for secondary use in stationary storage. 4 Existing Li-ion battery recycling capacity is being built out rapidly, running ahead of volumes of available scrap.[8]
Electrolysers and Fuel Cells	1 Continuous energy efficiency improvements for electrolysis, to reach <45 kWh/kgH2 by 2050.[9] 2 Continuous energy efficiency improvements for fuel cells, reaching 60% by 2050.[10] 3 Electrolysers are run at high load factors (e.g. 60% in 2020, falling only to 50% by 2050), to reduce material requirements for new capacity. 4 Continuous innovation to reduce PGM content of electrolysers without losing benefits of flexible loading, e.g. by developing hybrid Anion Exchange Membrane electrolysers.[11]	1 By 2040/50, over 70/90% of electrolysers and fuel cells are collected for recycling at end-of-life. 2 Recycling of electrolysers and fuel cells depends strongly on the value of embedded material content. Paradoxically, as innovation reduces requirements for PGMs, this would also likely reduce the potential monetary value of recycled content.
Nuclear	1 Improved management, operation and maintenance schedules allow average nuclear fleet capacity factors to remain above 85% through to 2050. 2 There are a wide variety of next-generation and small modular nuclear reactors in development, which have the potential to reduce material requirements, especially for uranium fuel.[12]	1 There is potential for re-purposing/recycling of spent nuclear fuel, e.g. into mixed-oxide fuel, which can then be used in certain types of nuclear reactors. Up to 96% of re-usable material in spent fuel can be recovered.[12] 2 Nuclear fuel is currently extensively recycled and reprocessed in this way in France.[12]

SOURCE: [1] NREL (2022), *Utility-scale PV*; BNEF (2023), *Transition metals outlook* [2] Walzberg et al. (2021), *Role of the social factors in the success of solar photovoltaic reuse and recycling programmes*; [3] BNEF (2020), *35MW Wind turbines to lower material demand*; [4] Wind Europe (2020), *Accelerating wind turbine blade circularity*; [5] ENTSO-E Technopedia (2023), *Dynamic line rating*; [6] BNEF (2020), *Copper and aluminium compete to build the future power grid*; Canary Media (2022), *How to move more power with the transmission lines we already have*; [7] Pampel et al. (2022), *A systematic comparison of the packing density of battery cell-to-pack concepts at different degrees of implementation*; [8] Bloomberg (2022), *The next big battery material squeeze is old batteries*; [9] IRENA (2020), *Green hydrogen cost reduction*; [10] US Department of Energy (2015), *Fuel cells fact sheet*; [11] Miller et al. (2020), *Green hydrogen from anion exchange membrane water electrolysis*; [12] BNEF (2022), *2H Nuclear market outlook*; IAEA (2019) *France's efficiency in the nuclear fuel cycle*.

2.3.1 Technology and materials efficiency – major potential impact by the 2030s

Among the most important actions to reduce demand via improved efficiency and innovation are [Exhibit 2.8]:

- **Improved load factors for wind farms**, requiring fewer installations, and therefore fewer materials, to generate the same TWh of electricity. Such improvements could reduce the installed capacity of wind in 2050 required to meet the ETC's decarbonisation pathway from 14 TW to 12 TW (15%).

- **Higher efficiency of solar, batteries and electrolysers** which reduces material intensity for copper, rare earth elements, silicon, and others in each solar panel, battery or electrolyser. For example, BNEF predict battery pack energy density could rise from 160 kWh/kg currently up to around 250 kWh/kg by 2030 –and providing the same vehicle range with around 35% lower material requirements.[53] Similarly, silicon intensity of solar panels is expected to keep falling over coming decades.[54]

- **Technological innovation and substitution for batteries**, which shifts to cobalt- and nickel-free battery chemistries and improving battery energy densities, reducing requirements for key battery materials. We estimate that a higher share for Lithium Iron Phosphate (LFP) and low-cobalt NMC[55] batteries could see projected cobalt demand in 2030 fall from around 430 kt to 290 kt (over 30%).

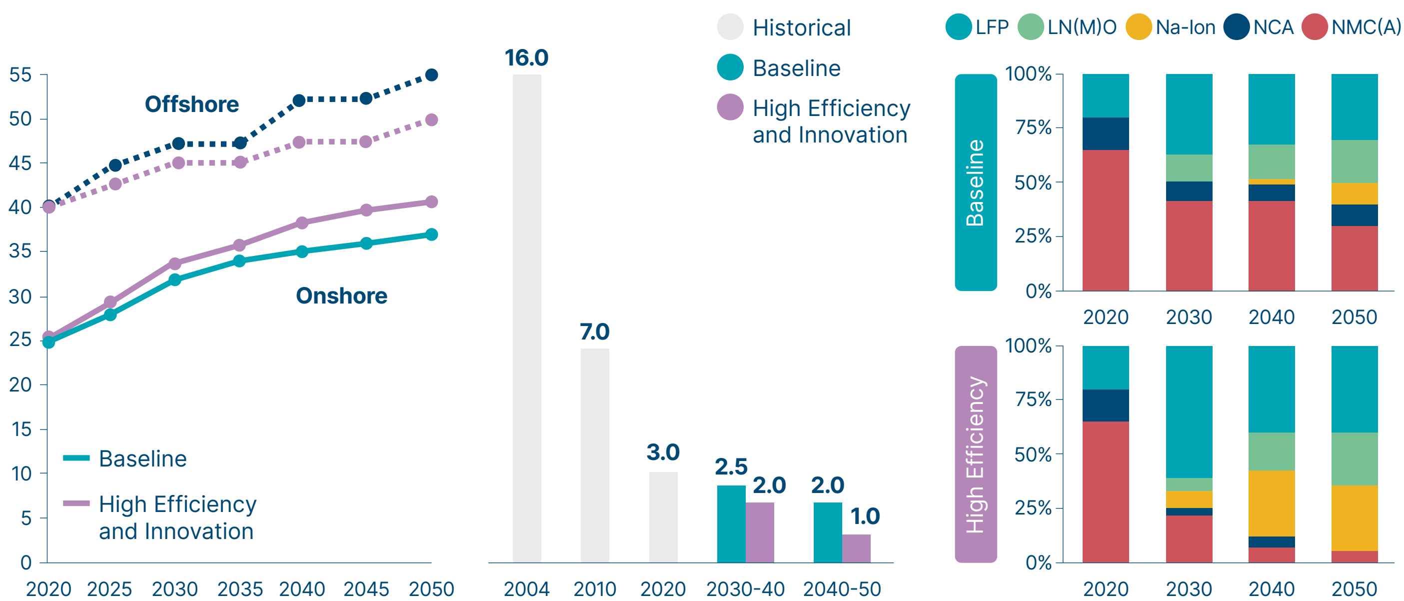
EXHIBIT 2.8

Improving technology performance, falling materials intensity, and new battery chemistries drive down material requirements

Technology performance: Wind turbine capacity factors
%

Materials efficiency: Silicon content of solar photovoltaics
g/W

Technology substitution: Passenger vehicle battery market shares by battery type[1], %



Improved capacity factors mean fewer installations (and therefore materials) for the same TWh of electricity.

Lower materials intensity of solar means less silicon is required to produce the same TWh of electricity.

Innovation in battery chemistries will see a shift towards cobalt- and nickel-free batteries.

[1] L = Lithium; F = Iron; P = Phsophate; N = Nickel; M = Manganese; O = Oxygen; Na = Sodium; C = Cobalt; A = Aluminium.

NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The High Efficiency scenario assumes accelerated progress in materials and technology efficiency.

SOURCE: Systemiq analysis for the ETC; BNEF (2021), *New energy outlook*; Fraunhofer ISE (2022), *Photovoltaics Report*; BNEF (2022), *Long-term electric vehicle outlook*.

53 BNEF (2022), *Long-term electric vehicle outlook*. Various battery manufacturers have announced plans to go much further – see e.g., CATL (2023), *CATL launches condensed battery with an energy density of up to 500 Wh/kg, enables electrification of passenger aircrafts*.

54 BNEF (2023), *Transition metals outlook*.

55 Nickel-Manganese-Cobalt (NMC).

These, and other actions across the full spectrum of materials and technologies, would significantly reduce material requirements. In particular:

- **Steel:** Where cumulative energy transition related steel demand between 2023–50 could fall from around 4,900 Mt to 3,700 Mt (a 25% reduction), predominantly as a result of reduced requirements in wind and solar installations.

- **Aluminium:** Cumulative requirements could fall from 950 Mt to 730 Mt (20% reduction), mainly driven by lower aluminium use in overhead cabling and mountings for solar panels.

- **Copper:** Cumulative demand could fall from 600 Mt to 420 Mt (30% reduction), driven by a combination of reduced use in grids, a reduced build-out of wind and solar installations, and lower copper intensity in electric vehicles.

In addition, and crucially, they would significantly reduce the likelihood and severity of supply gaps this decade. For the key materials with the biggest supply risks, improved technology performance and management, faster declines in material intensity, and substitution to alternative materials and technologies offer significant potential [Exhibit 2.9]:

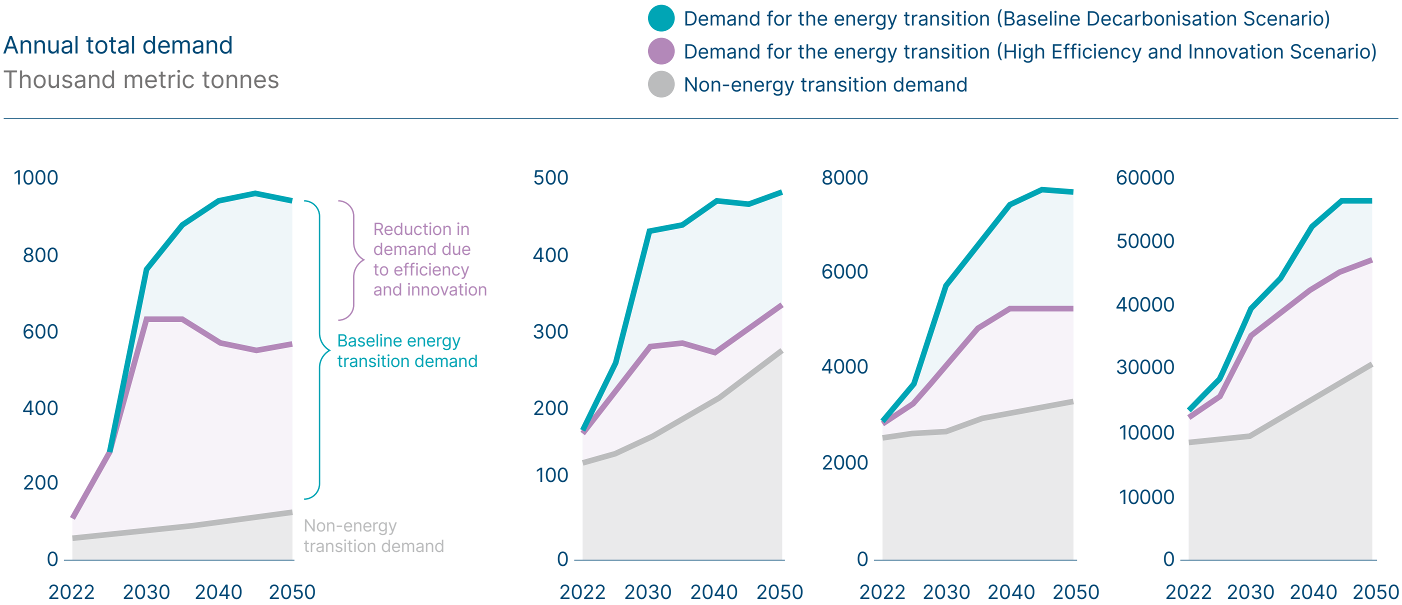
- **Lithium:** A shift to sodium-ion batteries beyond 2030, combined with faster battery energy density improvements and slower growth in battery pack sizes leads to a 40% reduction in demand by 2050, with demand in that year cut from around 940 kt to 570 kt.

- **Cobalt and nickel:** The rapid rise of LFP batteries displaces significant demand from cobalt- and nickel-rich battery compositions, reducing future materials demand projections, especially over the short term to 2030. Faster battery energy density improvements and slower growth in battery pack sizes also help mitigate demand increases.

- **Copper:** Larger wind turbines, more efficient solar panels, and better siting and management, can help generate more terawatt hours of electricity with less copper. Improvements in grid management and digitalisation, reducing redundancy requirements, and improving smart demand management can also help reduce the scale of the grid build-out required and its demand for copper.

EXHIBIT 2.9

Demand from the energy transition can be reduced through technology and materials efficiency



<table>
<tr><th></th><th>Lithium</th><th>Cobalt</th><th>Nickel</th><th>Copper</th></tr>
<tr><td rowspan="3">Drivers of efficiency</td><td colspan="3">Improving battery energy density, better packing efficiency, to achieve higher range for same materials.</td><td rowspan="3">Improving efficiency, capacity factors for wind and solar, reduces need for installations and copper intensity.

Shift to aluminium in certain cases for power cables.

Digitalisation, smart demand management, power flow routing help reduce required size of grid build-out.</td></tr>
<tr><td colspan="3">Smaller batteries in BEVs; average battery in passenger vehicles stays at ~55 kWh, e.g. via tax on SUVs or large batteries.</td></tr>
<tr><td>Development of sodium-ion batteries, growing to take 30% of market by 2040.</td><td>Rapid shift to low-cobalt NMC and LFP batteries in 2020s and 2030s.</td><td>Rapid shift to LFP batteries in 2020s and 2030s, >50% of market in 2025-35.

Lower nickel intensity in electrolysers.

Lower nickel-alloyed steel intensity of wind turbines.</td></tr>
</table>

NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The High Efficiency scenario assumes accelerated progress in materials and technology efficiency. Non-energy transition demand is held constant across all scenarios. The efficiency levers are only applied to demand for the energy transition.

SOURCE FOR ENERGY TRANSITION DEMAND: Systemiq analysis for the ETC. LFP = Lithium-Iron-Phosphate; NMC = Nickel-Manganese-Cobalt.

SOURCES FOR NON-ENERGY TRANSITION DEMAND: Lithium – IEA (2021), *The role of critical minerals in clean energy transitions*; Cobalt – Ibid.; Nickel – BNEF (2023), *Transition metals outlook*; Copper – BNEF (2022), *Global copper outlook 2022-40.*

Some of these trends are already taking place, driven by high prices and continuous innovation [Exhibit 2.10]:

- The ongoing shift to low-cobalt nickel-manganese-cobalt (NMC) and cobalt-free LFP batteries has driven down forecasts of future cobalt demand in 2030 by over 50%.[56]
- In certain cases, when copper prices are high enough and project specifications allow it, switching to aluminium for power cables has taken place – reducing copper demand by 200–500 kt each year between 2005–18.[57]

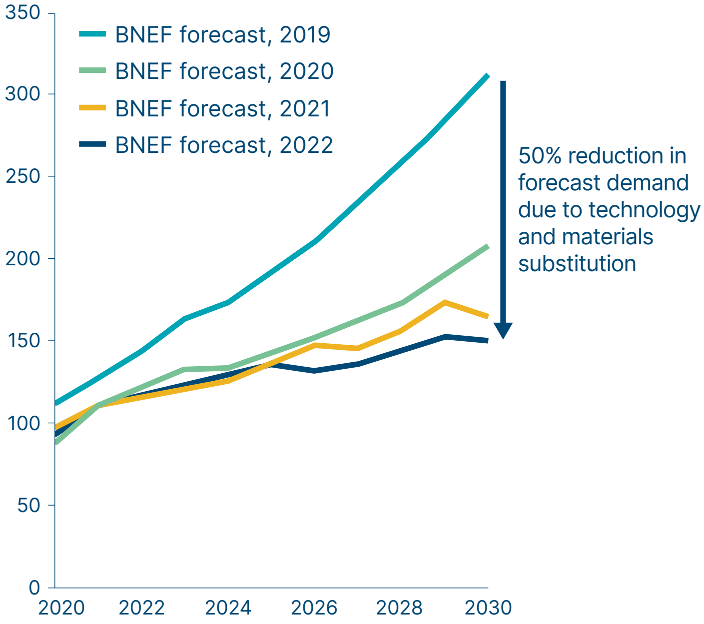
Finally, as an illustration of the potential for a very different style of low-carbon power generation system, Box C outlines the trade-offs between land use, material requirements and costs associated with an increased use of nuclear power.

56 BNEF (2022), *Long-term electric vehicle outlook.*
57 BNEF (2020), *Copper and aluminium compete to build the future power grid.*

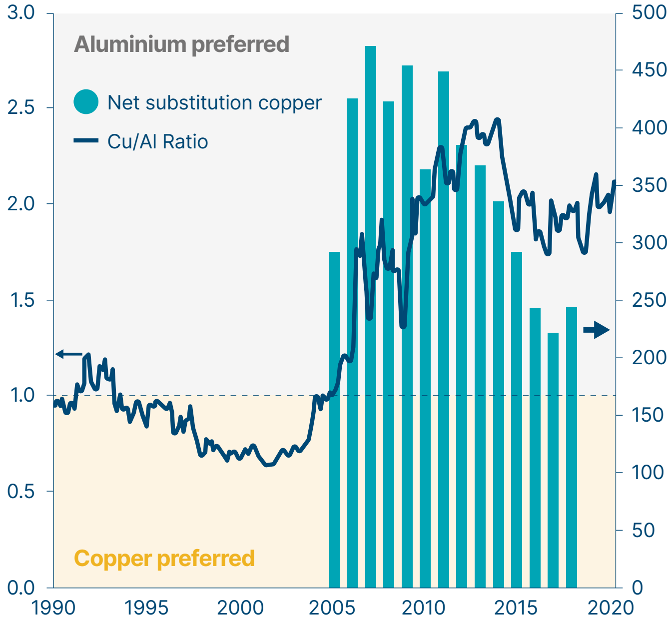
EXHIBIT 2.10

Technology and material substitution is already happening: projected demand for cobalt has fallen dramatically, and high copper prices incentivise a switch to aluminium in grids

Projected cobalt demand
Thousand metric tonnes

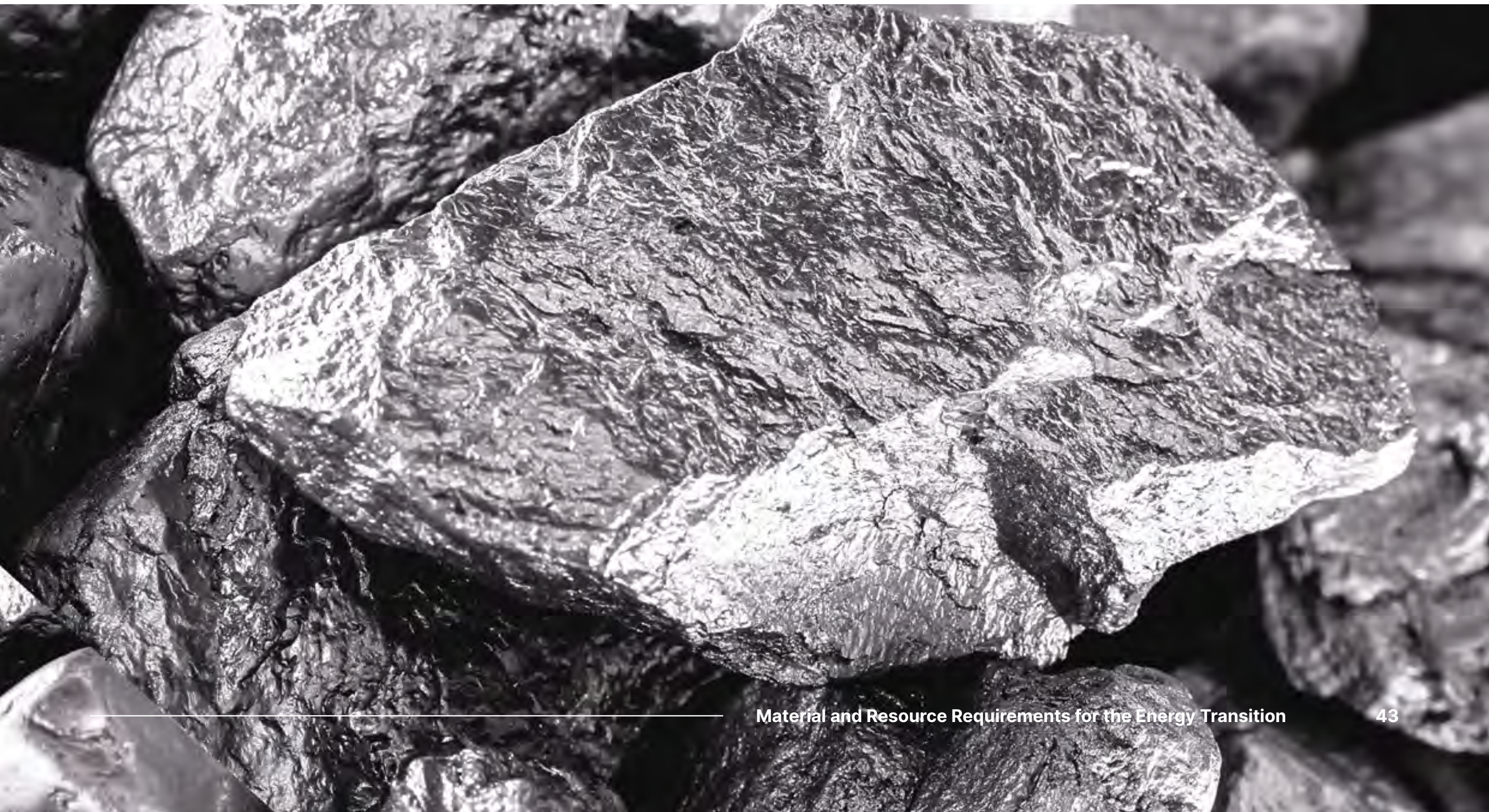


Adjusted average copper-to-aluminium price ratio[1] (LHS) and net substitution of copper (RHS)
US$/kg (LHS); Thousand metric tons (RHS)



[1] Ratio of prices is adjusted to account for higher conductivity (a ratio of 1.66:1 Cu:Al). A value above 1 indicates aluminium is favoured over copper.

SOURCE: BNEF (2022), *Long-term electric vehicle outlook*; BNEF (2021), *Copper and aluminium compete to build the future power grid.*



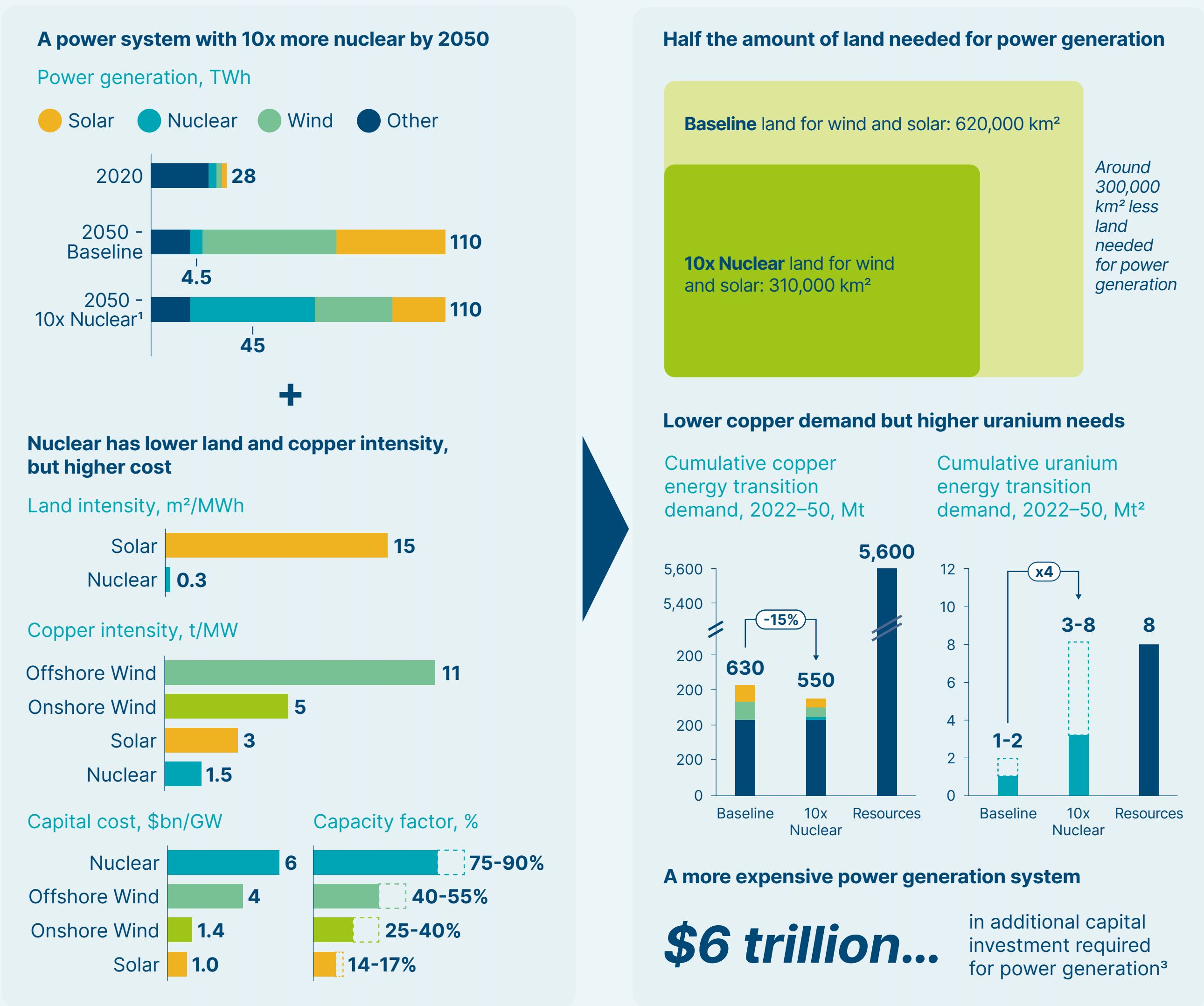
BOX C: What if we increased nuclear power generation 10x?

Nuclear power generation does in general have lower material intensity than solar and wind power,[58] as well as much lower land use requirements (for both mining of materials and siting/operation).[59] However, nuclear power is also associated with much higher capital investment requirements than wind and solar, several times higher than solar.[60] It would also require a expansion of uranium extraction, potentially reaching levels associated with currently estimated reserves if extensive spent fuel recycling, or shifts to alternative fuels, did not become widespread.

Expanding nuclear capacity could be an option to reduce the requirements of land and raw materials from the build-out of wind and solar for power generation. Exhibit 2.11 illustrates a scenario where nuclear power plays a much larger role than expected, which could help alleviate materials requirements but would lead to significantly higher investment requirements in power generation. These trade-offs would need careful consideration in order to weigh up the benefits of one particular technology over another.

EXHIBIT 2.11

Scaling the use of nuclear power could reduce land use and copper needs – but would come with high uranium demand and a higher cost for the power generation system



¹ Assumes that increased nuclear generation directly replaces only wind and solar, split 50:50. ² Range depends on scale of uranium recycling, uranium fuel loading of reactors and the ramp-up in nuclear generation over coming decades. ³ Calculated as the difference in capital investment needs for wind, solar and nuclear capacity in the Baseline and 10x Nuclear scenarios, and using capital investment costs from Lazard (2023), *Levelised cost of energy analysis – Version 15.0* and from Lovering et al. (2016), *Historical construction costs of global nuclear power reactors*. This does not account for differences in storage or grid investments.

SOURCE: Systemiq analysis for the ETC; Our World in Data (2022), *Land use of energy sources per unit of electricity*; UNECE (2021), *Lifecycle assessment of electricity generation options.*

58 See e.g., IEA (2021), *The role of critical minerals in clean energy transitions;* IEA (2023), *Energy technology perspectives.*

59 Our World in Data (2022), *How does the land use of different electricity sources compare?*

60 Lazard (2023), *Levelised cost of energy analysis – Version 15.0*; Lovering et al. (2016), *Historical construction costs of global nuclear power reactors.*

2.3.2 Increased recycling – small potential to 2030 but very large by 2040s

By 2050, its plausible that the majority of new demand requirements from clean energy technologies could be met through secondary supply. But over the short-term to 2030, less than 10% of demand from the energy transition is likely to be met through recycling. This is because:

- **Existing end-of-life recycling rates are currently low and will take time to increase:** Current levels of recycling vary significantly across materials, with aluminium, steel and copper quite widely recycled, as well as certain highly valuable metals such as platinum [see Box D and Exhibit 2.12]. Many key battery materials, however, have low recycling rates; this is especially the case for lithium, where low collection and technical challenges make recovery of lithium difficult or prohibitively expensive and mean less than 1% is recycled at end of life.[61]

- **Timescales for stock turnover of clean energy technologies:** Secondary supply can only be scaled up as clean energy products reach end of life. This means that much of the lithium, copper or silicon in use in batteries, grids and solar panels that is sold in the coming years will not become available for decades.

Over the long term, however, there is significant potential to improve recycling and waste management rates for a range of products and processes, with a major impact on the volume of primary supply required, but only from 2040 onwards [Exhibit 2.13]. Accelerating recycling on its own will not be sufficient to close supply gaps in 2030.

BOX D: The current status of recycling

Although many comparisons are made with recycling from electronic waste, clean energy technologies tend to be large, industrial machinery – making the potential for recycling much more comparable to recycling from heavy industry where collection rates are high, such as for grid infrastructure or vehicles.[62]

Two key factors underpin high recycling levels: high value/prices for materials, and the existence of business-to-business models. As soon a system shifts to consumer-facing models more individual incentives need to be aligned, making recycling more challenging.[63]

Copper, aluminium and steel are commonly recycled – for example, secondary supply of Aluminium is around 35% of total supply currently [Exhibit 2.12, LHS].[64] However, current recycling rates for lithium and rare earth elements (including neodymium) are very low – technical efficiency improvements are needed alongside a concerted effort to improve end-of-life collection.

For batteries, three factors are key to recycling effectively: the battery chemistry (which dictates embedded value of materials), the recycling approach (which determines recovery rates and operating costs), and the location of recycling [Exhibit 2.12, RHS].

Battery recycling capacity is already expanding rapidly – to the point where over-capacity is possible, with 750 kt p.a. of recycling capacity expected in 2030 but supply of only around 320 kt p.a. of scrap available as battery manufacturers push to reduce waste during production.[65]

There is also strong potential to increase secondary supply of materials from non-energy transition sources of material use. This is especially the case for copper, where approximately 460 Mt of copper are currently in use across the already-built power system, transport, buildings, appliances and more.[66] For example, there could be up to 30 Mt of copper in existing power plants,[67] a large fraction of which could be recovered as coal- and gas-fired power plants are decommissioned.

Improvements in the collection and recycling of copper at end of life within clean energy technologies could result in secondary supply growing to reach over 7 Mt by 2050, meeting over 40% of total energy transition demands. But if more copper could be recovered from existing sources and recycled or re-used, incentivised by high prices and/or regulation, an even higher fraction of future demand for copper could be met from the existing stock of copper in the wider economy.

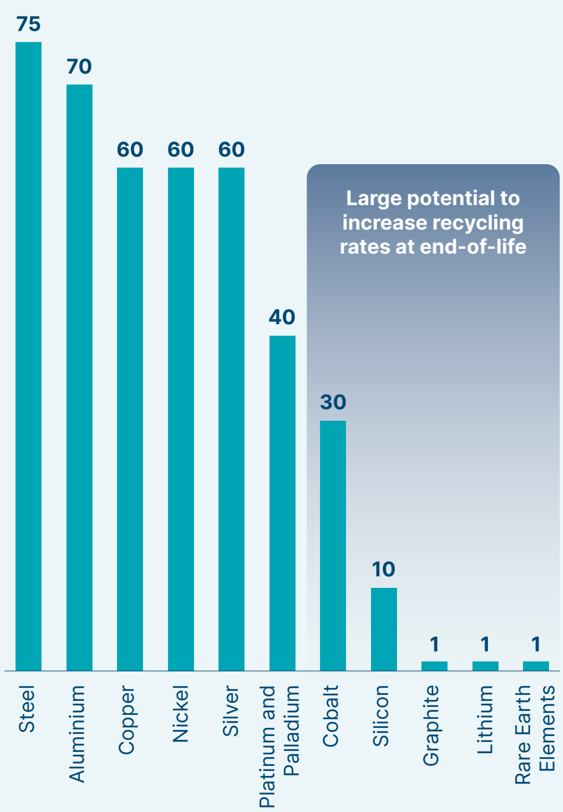
61 Lander et al. (2021), *Financial viability of battery recycling.*
62 Wang et al. (2018), *Copper recycling flow model for the United States economy*; Hagelüken and Goldmann (2022), *Recycling and circular economy – towards a closed loop for metals in emerging clean technologies.*
63 Hagelüken and Goldmann (2022), *Recycling and circular economy – towards a closed loop for metals in emerging clean technologies.*
64 MPP (2022), *Making net-zero aluminium possible.*
65 Bloomberg (2022), *The next big battery material squeeze is old batteries.*
66 Copper Alliance (2022), *Copper Recycling.*
67 Kalt et al. (2021), *Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus.*

BOX D: The current status of recycling

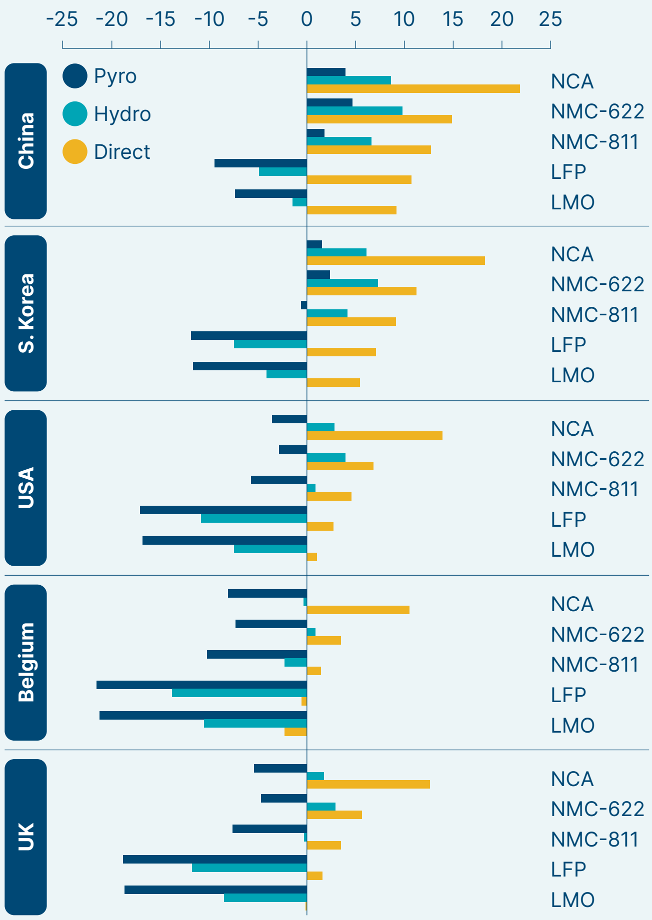
EXHIBIT 2.12

Current recycling rates for some energy transition materials are low; recycling LFP and LMO batteries faces strongest challenges

End-of-life recycling rate
Global average, %



Net battery recycling profit[1]
$/kWh



[1] For a 240 Wh/kg battery, and includes transportation (starting in the UK), disassembly, recycling costs and revenues generated from resale of materials from both cells and packs. NCA = Nickel-Cobalt-Aluminium; NMC = Nickel-Manganese-Cobalt; LFP = Lithium-Iron-Phosphate; LMO = Lithium-Manganese-Oxide. Pyro = pyrometallurgy, a heat-based extraction and purification process; Hydro = hydrometallurgy, a process that involves dissolving and recovering metals in solutions; Direct battery recycling involves shredding a battery to separate components, without breaking down the chemical structure of key active materials in the anode and cathode.

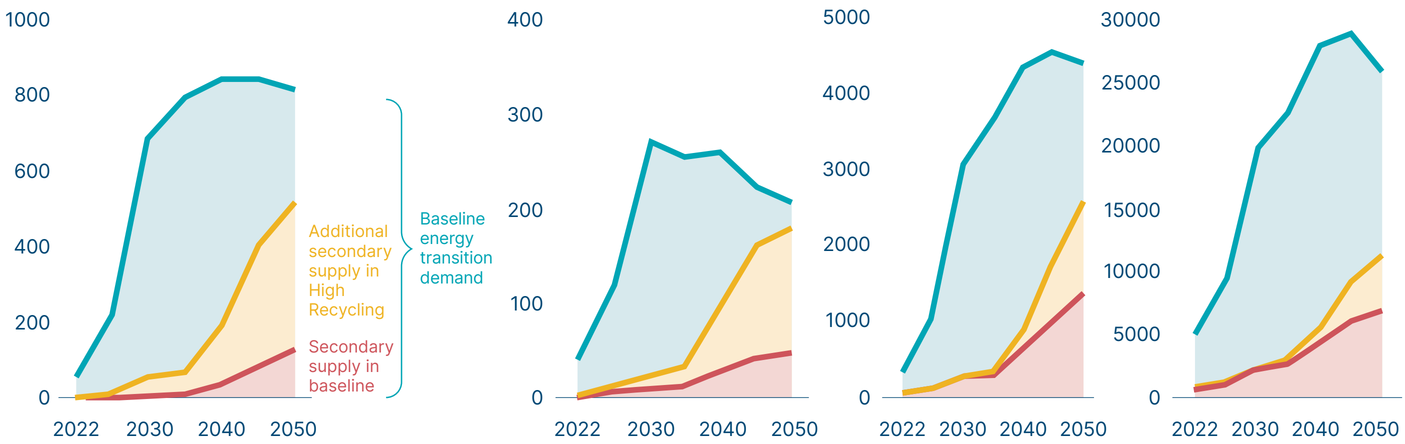
SOURCE: Systemiq analysis for the ETC; IEA (2021), *The role of critical minerals in clean energy transitions*; Lander et al. (2021), *Financial viability of electric vehicle lithium-ion battery recycling.*

EXHIBIT 2.13

Recycled supply will remain low in 2030, but could be significant from 2040s onwards

Annual energy transition demand and secondary supply
Thousand metric tonnes

- Energy transition demand (Baseline Decarbonisation scenario)
- Secondary Supply (Baseline Decarbonisation scenario)
- Secondary Supply (High Recycling scenario)



	Lithium	Cobalt	Nickel	Copper
Drivers of recycling	Increase collection of batteries at end of life, reaching 80/90% by 2040/50.			Improving collection at end-of-life across all clean energy technologies, with a particular focus on grids being repaired/replaced and on vehicles at end-of-life. Increasing copper recycling at end-of-life from ~60% currently to 90% by 2040.
	Expand battery recycling capacity to handle >1 Mt of battery materials by 2030, >5 Mt by 2050.			
	Improve lithium recycling at end-of-life from ~1% currently to 90% by 2040.	Improve nickel recycling at end-of-life from ~60% currently to 90% by 2040.	Improve cobalt recycling at end-of-life from ~30% currently to 90% by 2040.	

NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The High Recycling scenario assumes accelerated progress in recycling clean energy technologies and recovering materials. Secondary supply only measures that from clean energy technologies.

SOURCE: Systemiq analysis for the ETC.

By the late 2040s [Exhibit 2.14]:[68]

- Over 50% of energy transition demand could be met by recycled supply for three key battery materials: cobalt, graphite and lithium. This would follow from a major ramp-up in end-of-life collection, with over 80% of batteries being collected at end of life from 2040 onwards, and high recycling rates of 90% from 2030 onwards (85% for lithium).[69]

- In the case of copper or aluminium, secondary supply would be able to meet 30–40% of energy transition demand – somewhat lower, but still a significant share. For both materials, and especially for copper, there is also strong potential to expand recycling from other sources of demand [Box D].

- For other materials, such as silicon or steel, long technology lifetimes (e.g., 30 years for a solar or wind farm) mean that volumes of secondary supply from clean energy technologies would remain low even in 2050 – but with strong potential in subsequent years.

68 These estimates do not account for potential secondary supply from non-energy transition sources – which could increase significantly over coming decades as well for e.g., copper or aluminium, but is out of the scope of this report.
69 Circular Economy Initiative Deutschland (202), *Resource-efficiency battery life cycles.*

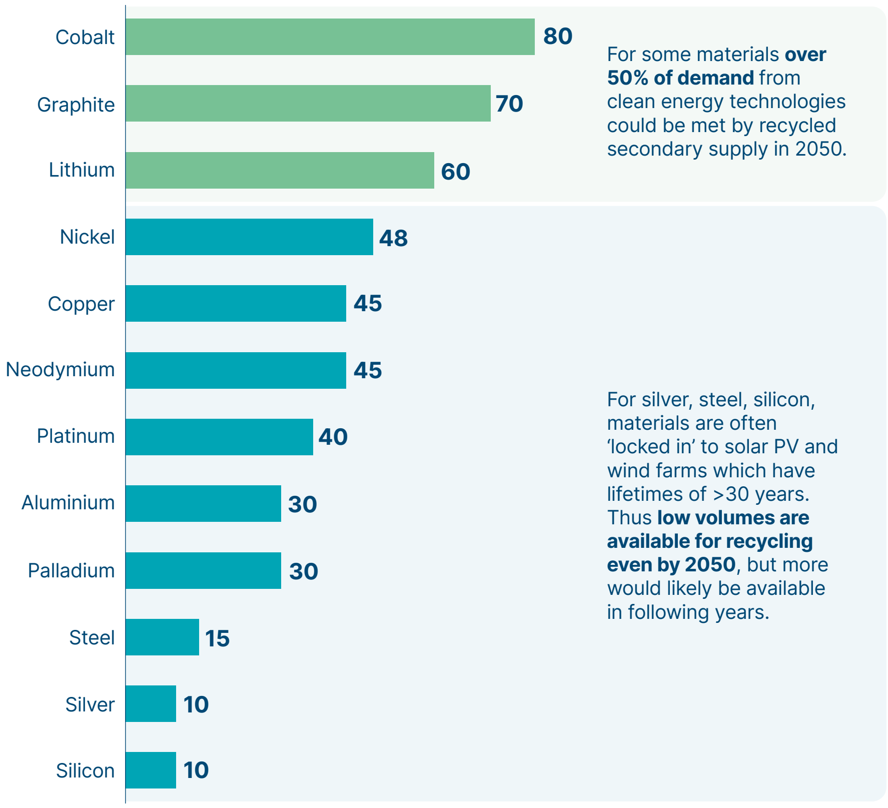
By 2050, its plausible that the majority of new demand requirements from clean energy technologies could be met through secondary supply [Exhibit 2.14]. However, strong action is required throughout the 2020s to ensure that policy, incentives and infrastructure are in place to scale-up the role of recycling significantly in coming decades – especially for batteries [Box E]. These actions are discussed in Section 2.5 below.

EXHIBIT 2.14

With improving policies, logistics and infrastructure, recycling has the potential to serve large shares of key material requirements by 2050

Average share of annual materials demand for the energy transition that could be met by secondary supply (High Recycling scenario), 2050

%



Criteria for policy intervention to support recycling

- Where significant **supply shortages** are likely.
- Where recycling can **reduce environmental impacts** significantly relative to mining.
- Where **landfill is not appropriate** (e.g. due to risk of toxic waste).

Actions to scale recycling

- **Create a market** for secondary materials, via regulation or incentives.
- Increase rates of **waste collection** at end-of-life.
- **Improve design** to make recycling easier.
- **Increase efficiency**/yield of recycling processes.

NOTE: Uranium is not included due to the strong uncertainty around scale of future use of recycled fuel in nuclear reactors and uncertainty around recycling rates. The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The High Recycling scenario assumes accelerated progress in recycling clean energy technologies and recovering materials.

SOURCE: Systemiq analysis for the ETC.

Box E: The importance of recycling – of batteries in particular

The importance and prevalence of recycling across clean energy technologies will depend on recoverable material value, available logistics and infrastructure, and costs.

For wind turbines and solar panels, large-scale recycling is feasible and should be strongly encouraged – but landfill volumes would be small and manageable even if widespread recycling were not economic:

- In the case of wind turbines, up to 90% of a wind turbine's mass can be recycled (excluding the concrete base), and there are established recycling systems for the foundation, tower and parts of the nacelle.[70] The key challenge remains recycling of turbine blades, but even here innovation is taking place to use new advanced composites that can be more easily recycled.[71] Similarly for solar panels, over 90% of materials can be recovered and recycled or re-used in other sectors.[72]

- Even if no recycling took place, however, the mass of solar panel materials reaching end-of-life in 2050 would be around 20 million tonnes of waste globally.[73] For wind, by 2050 there would be just 100,000 tonnes of wind turbine blades reaching end-of-life. Such waste should ideally re-used or recycled, but if it was placed in landfill the total mass would be low and manageable compared with around 200 million tonnes of metals and glass waste produced currently, and total global waste production of up to 3.4 billion tonnes by 2050.[74]

For batteries the picture is different. The objective should be close to 100% re-use or recycling, given the high cost of primary mineral inputs, the potential for supply bottlenecks to constrain demand growth, and the significant environmental impacts of mining – challenges which are much lower for solar and wind. Close to total recycling is already technically feasible, and the high cost of primary minerals creates strong economic incentives for it to be deployed. In the case of NMC batteries (which include cobalt and nickel as well as lithium) extensive recycling would occur even without regulation; by contrast LFP batteries (where only the lithium is highly valuable), might not be fully recycled without strong regulation.[75]

Strong public policy should therefore require that EV batteries are either re-used in stationary storage applications or almost entirely recycled. Policies already in place and needed to achieve this are discussed in Chapter 2, Section 2.5.3.

2.3.3 Combined effect of efficiency and recycling

Combining efficiency and recycling could see demand for primary materials extraction fall by 20% (silver) to up to 80% in some cases (cobalt). Exhibit 2.15 sets out projected demand under the Maximum Efficiency and Recycling scenario. Compared with the Baseline Decarbonisation scenario [Exhibit 2.4], this results in reductions in cumulative primary demand from the energy transition, as shown in Exhibit 2.16, of:

- Demand for primary steel down nearly 30%, for aluminium down 25%, and for copper down 40%.

- For battery materials, shorter battery lifetimes and a large potential increase in end-of-life recycling (from near-zero levels) mean reductions in primary demand could be very large: primary cobalt demand falls by nearly 80%, nickel demand falls by nearly 60%, lithium 55%, and graphite nearly 50%.

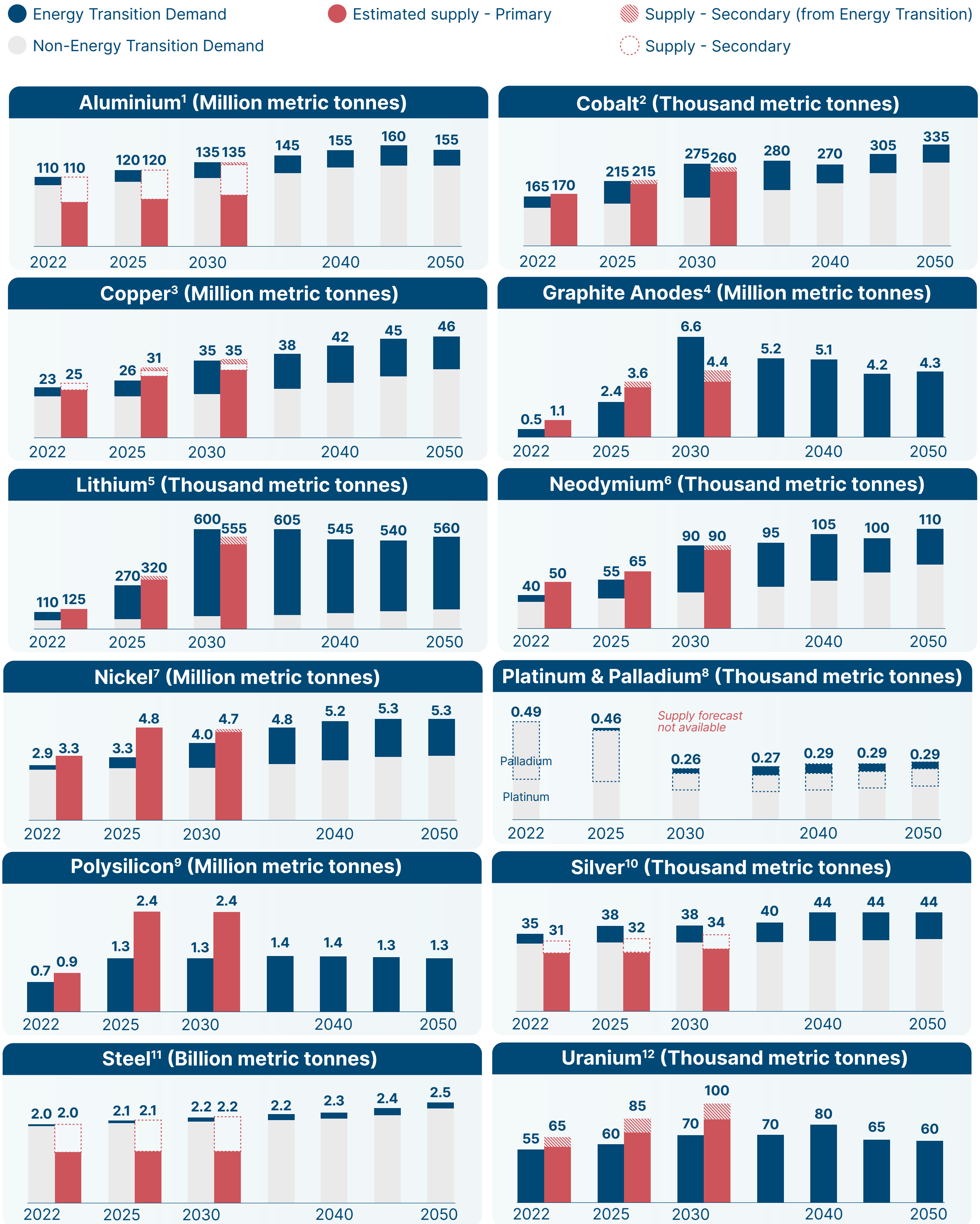
- A range of reductions from 20% to 60% for other energy transition materials.

As an example, Exhibit 2.17 sets out the potential primary demand reduction for nickel across the different efficiency and recycling levers included in this study. Cumulative primary demand to support the energy transition could fall by over 50%, cutting total primary nickel demand by 30%. These reductions derive primarily from a shift to nickel-free battery chemistries, smaller batteries, improvements in battery energy density, and increased recycling. (Similar analysis is available for cobalt, copper, graphite, lithium and neodymium in our accompanying Material Factsheets.)

70 Wind Europe (2020), *Accelerating wind turbine blade circularity.*
71 Ibid.
72 Heath et al. (2020), *Research and development priorities for silicon photovoltaic module recycling to support a circular economy*; Engie (2021), *How are solar panels recycled?*
73 For wind, assuming 100 GW reach end-of-life, an average turbine capacity of 10 MW, and an average mass of around 3.5 tonnes per wind turbine blades. For solar, assuming around 200 GW of solar reaching end-of-life, and a material mass intensity of around 100 t/MW (excluding concrete). Systemiq analysis for the ETC, based on Wind Europe (2020), *Accelerating wind turbine blade circularity*; Heath et al. (2020), *Research and development priorities for silicon photovoltaic module recycling to support a circular economy*; Carrara et al./EU JRC (2020), *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonized energy system.*
74 World Bank (2018), *Trends in solid waste management.*
75 Lander et al. (2021), *Financial viability of electric vehicle lithium-ion battery recycling.*

EXHIBIT 2.15

Maximum Efficiency and Recycling: Annual material demand and supply



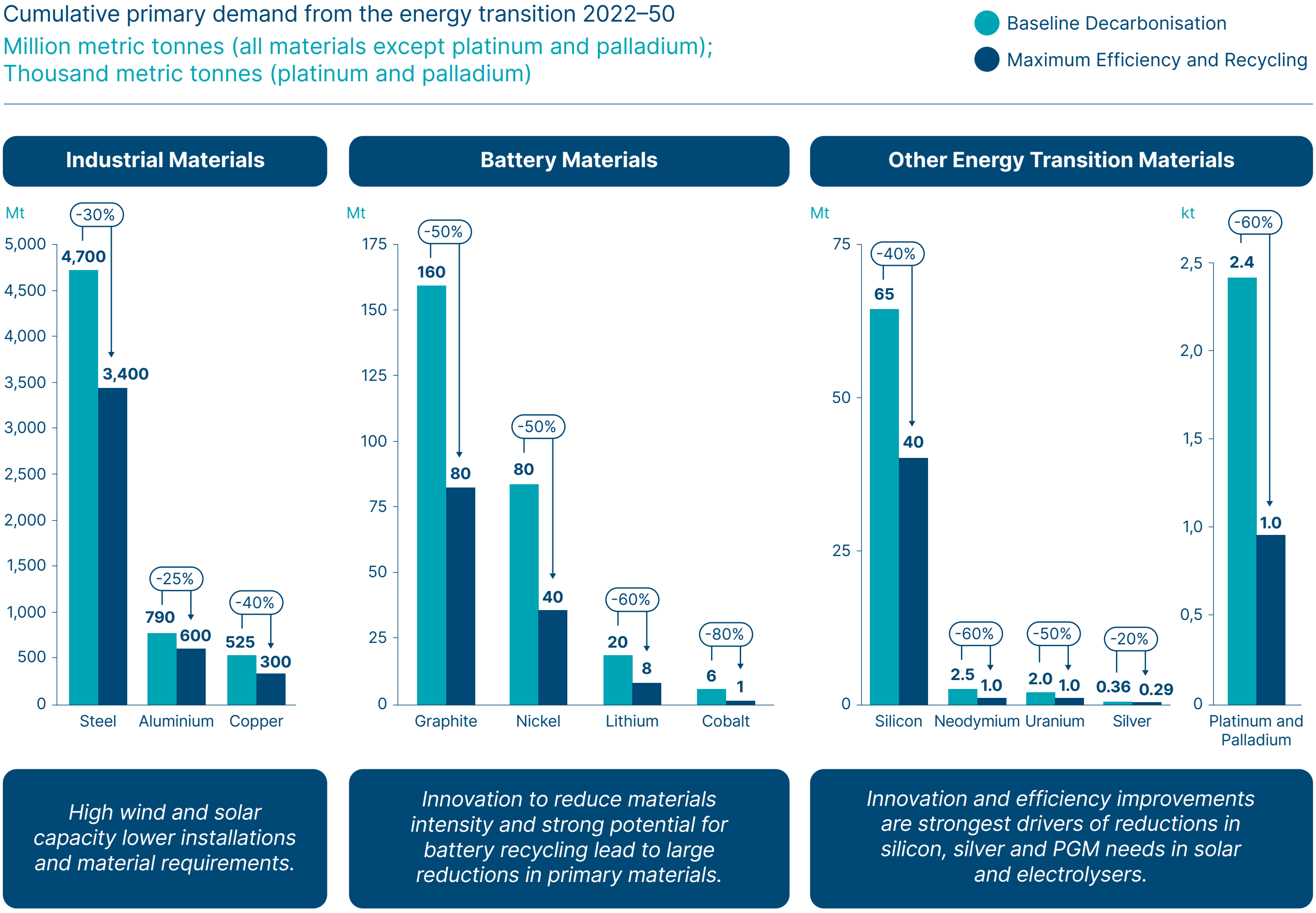
SOURCE: [1]Non-energy demand and secondary supply from Mission Possible Partnership/International Aluminium Institute, primary supply from BNEF (2023), *Transition metals outlook*; [2]Non-energy demand from IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, supply from BNEF (2022), *2H Battery Metals Outlook*; [3]Non-energy demand from BNEF (2022), *Global Copper Outlook*, primary supply from BNEF (2023), *Transition metals outlook*, secondary supply from non-energy transition is assumed to be 10% of primary supply; [4]Supply from BNEF (2022), *2H Battery Metals Outlook*; [5]Sources same as for Lithium; [6]Non-energy demand from IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*, supply estimated assuming CAGR in REO production from 2010–21 continues to 2030, with neodymium making up 17% total supply; [7]Non-energy demand and supply from BNEF (2023), *Transition metals outlook*; [8]Non-energy demand modelled from phase-out of ICE cars, adding other sector demand, following BNEF (2021), *2H Hydrogen Market Outlook*; [9]Supply from BNEF (2023), *1Q Global PV Market Outlook*; [10]Non-energy demand and supply from Silver Institute (2022), *World Silver Survey*, extrapolated to 2050/30; [11]Non-energy demand and primary/secondary supply from Mission Possible Partnership; [12]Supply from World Nuclear Association (2021), *The Nuclear Fuel Report: Expanded Summary*.

EXHIBIT 2.16

Efficiency and recycling can reduce primary material requirements significantly – but more innovation and policy is needed

Cumulative primary demand from the energy transition 2022–50

Million metric tonnes (all materials except platinum and palladium); Thousand metric tonnes (platinum and palladium)



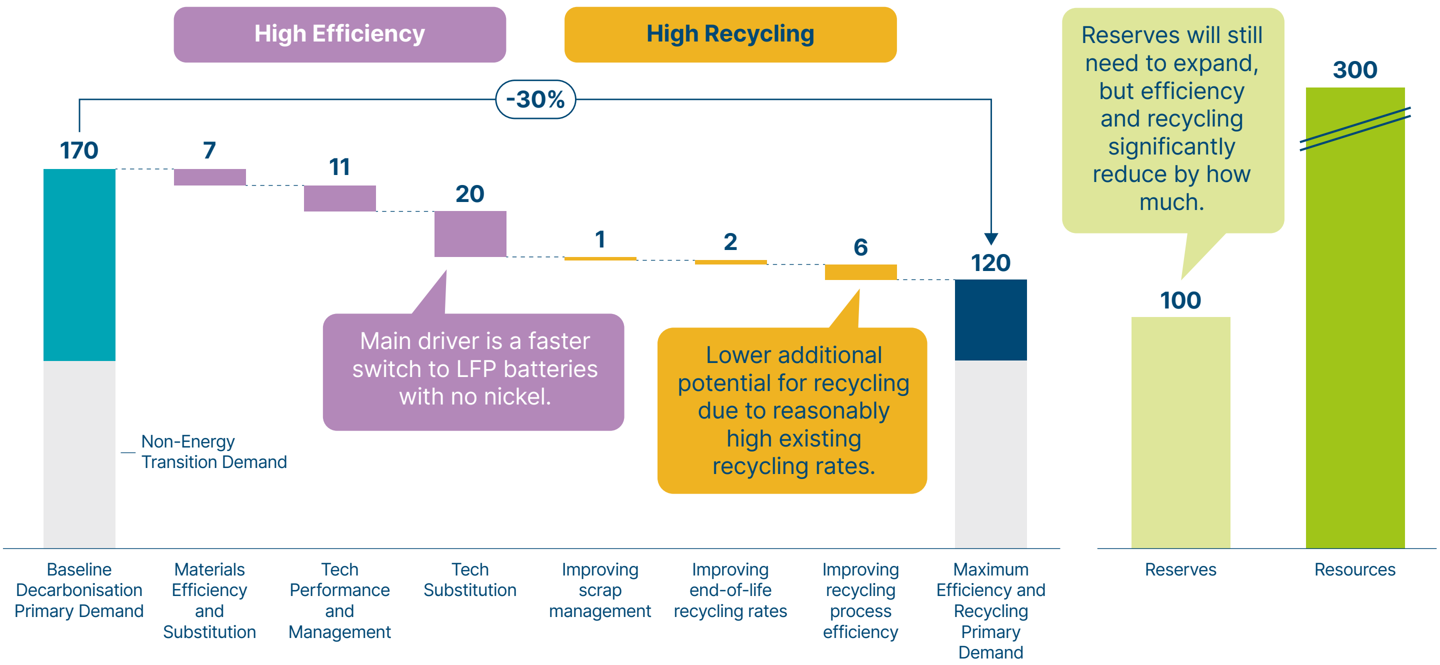
NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The Maximum Efficiency and Recycling scenario assumes accelerated progress in material and technology efficiency, and recycling of clean energy technologies/materials, thereby reducing requirements for the primary (i.e., mined) supply of materials.

SOURCE: Systemiq analysis for the ETC.

EXHIBIT 2.17

Example: primary demand for nickel can be reduced by new battery chemistries, reducing nickel intensity of alkaline electrolysers, and more recycling

Nickel cumulative primary demand 2022–50, reductions due to efficiency and recycling levers, and resources and reserves
Million metric tons



NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The High Efficiency Scenario assumes accelerated progress in material and technology efficiency, while the High Recycling Scenario assumes much greater recycling of clean energy technologies. The Maximum Efficiency and Recycling scenario brings the assumptions in High Efficiency and High Recycling together.

2.3.4 Further potential demand reductions through energy productivity

Additionally, there is likely to be significant potential to further reduce future material demands through actions which go beyond technological innovation, material efficiency and recycling, by improving the efficiency of energy (e.g. by reducing electricity demand through appliance efficiency) and service consumption (e.g. by shifting more journeys to shared public transportation).

The ETC are covering this question in detail in coming months, but earlier analysis suggested that final energy demand in 2050 could be reduced by up to 30%.[76]

Some of the biggest potential opportunities, which the ETC is investigating this year, include:

- The potential to greatly improve energy efficiency of both existing building stock (e.g., retrofits to improve insulation and the replacement of gas boilers with heat pumps) and new builds (e.g., through materials efficiency).
- Shifts in consumer behaviour (e.g., car sharing, public transportation) and better urban design can lower individual passenger vehicle ownership.
- Various investments across the industrial sectors to electrify, develop energy/heat storage solutions, and improve the energy efficiency of motors, machinery and equipment.

76 Final energy demand could range from around 495 EJ in 2050, down to around 355 EJ if strong actions is taken to improve energy productivity. ETC (2020), *Making mission possible*. The ETC's detailed report on energy productivity is forthcoming in Q1 2024.

To illustrate the potential impact on materials, if the total fleet of EVs could be reduced by around 10% in 2050 (to around 1.3 billion vehicles), this could reduce cumulative lithium demand to 2050 from 22 Mt down to around 20 Mt – having knock-on impacts on annual demand-supply gaps, total life-cycle emissions of material extraction, and any local environmental impacts.

Clearly, if such actions were taken there could be further decreases in materials demand from clean energy technologies, beyond the efficiency and recycling measures outlined here. The potential for energy productivity will be covered in an upcoming ETC report.

2.4 Reserves and supply gaps with efficiency and recycling improvements

If the raw material demand reductions potentially available from greater materials and technology efficiency and increased recycling can be achieved, this will improve both the relationship between:

- Cumulative potential demand and known reserves.
- The balance between likely demand and planned supply in the next decade.

Yet even with maximum potential demand reductions, a significant expansion of supply will be essential for some key materials.

2.4.1 Impact on reserve adequacy

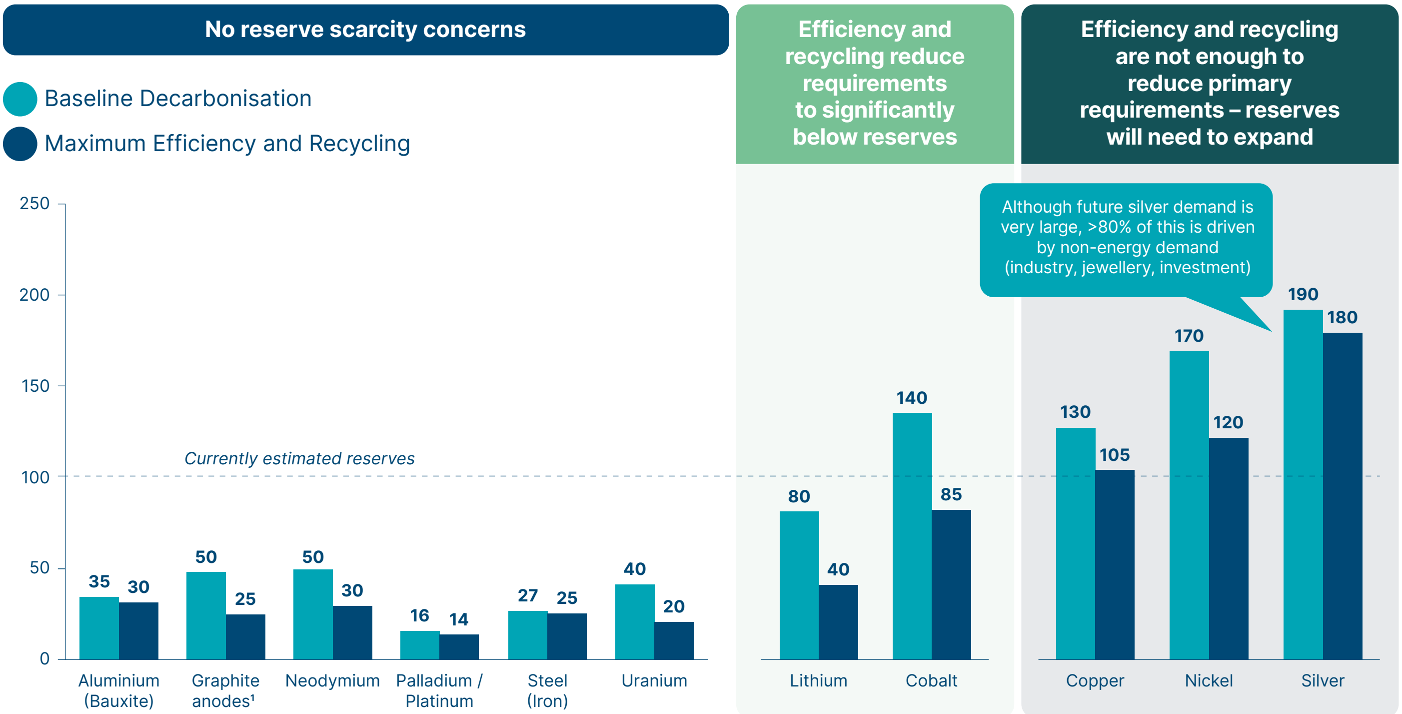
Chapter 1 compared currently assessed reserves and resources versus cumulative potential demand under the Baseline Decarbonisation scenario. Exhibit 2.18 shows the impact of achieving the Maximum Efficiency and Recycling scenario on reserve scarcity, and identifies three groups of materials:

- **No reserve scarcity concerns:** where even under the Baseline Decarbonisation scenario, cumulative primary materials demand is well below currently estimated reserves. This group includes aluminium, neodymium, steel, uranium and others.
- **Significant demand reduction to below current reserves:** These include lithium and cobalt, where under the Baseline Decarbonisation scenario, cumulative demand was either close to reserves (lithium) or significantly in excess (cobalt), but where improved efficiency, material substitution (e.g., cobalt-free batteries) and recycling can reduce primary demand well below reserves.
- **Demand reduction but still exceeding current reserves:** This group includes copper, nickel and silver where cumulative demand would still exceed currently assessed reserves even with strong action on efficiency and recycling. This implies increased exploration or development is needed to drive an expansion in exploitable reserves – or a major expansion in efficiency and recycling beyond what is expected.

EXHIBIT 2.18

Efficiency and recycling levers can mitigate total resource requirements for lithium and cobalt, but reserves would still need to expand for copper, nickel and silver

Cumulative primary demand 2022–50, as a percentage of known reserves
%



[1] Graphite reserves/resources refer to natural graphite, do not include synthetic graphite.

NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The Maximum Efficiency and Recycling scenario assumes accelerated progress in material and technology efficiency, and recycling clean energy technologies, thereby reducing requirements for the primary (i.e., mined) supply of materials.
Reserves are the currently economically and technically extractable subset of estimated total global resources in the earth's crust.

SOURCE: Systemiq analysis for the ETC.

2.4.2 Impact on supply gaps to 2030

Exhibit 2.15 shows how the Maximum Efficiency and Recycling scenario compares with planned supply growth to 2030 for all materials. Exhibit 2.19 focuses on the supply/demand balance in 2030 for the six key materials which are likely to face significant supply constraints in the Baseline Decarbonisation scenario.

In the case of nickel and copper, strong action to reduce total demand for materials, coupled with a small increase in secondary supply from energy transition technologies, could lead to a complete closure of the projected supply gaps in 2030. However, there may still be shortages for supply of high-purity nickel sulphate, the key refined input for battery cathodes [Box F].

However, supply gaps would remain for graphite, lithium, cobalt and neodymium:

- In the case of **graphite**, the risks associated with supply gaps is somewhat lower, as production of synthetic graphite (alongside natural graphite, which is mined) can ramp up quite quickly.
- For **neodymium**, the potential supply gap is small and there is increased potential for electric vehicles and wind turbines to shift to entirely rare-earth free motors, although these would require accelerated development.[77]

77 See e.g. US Department of Energy (2019), *Advanced wind turbine drivetrain trends and opportunities;* Adamas Intelligence (2023), *Implications: Tesla announces next generation rare-earth-free PMSM.*

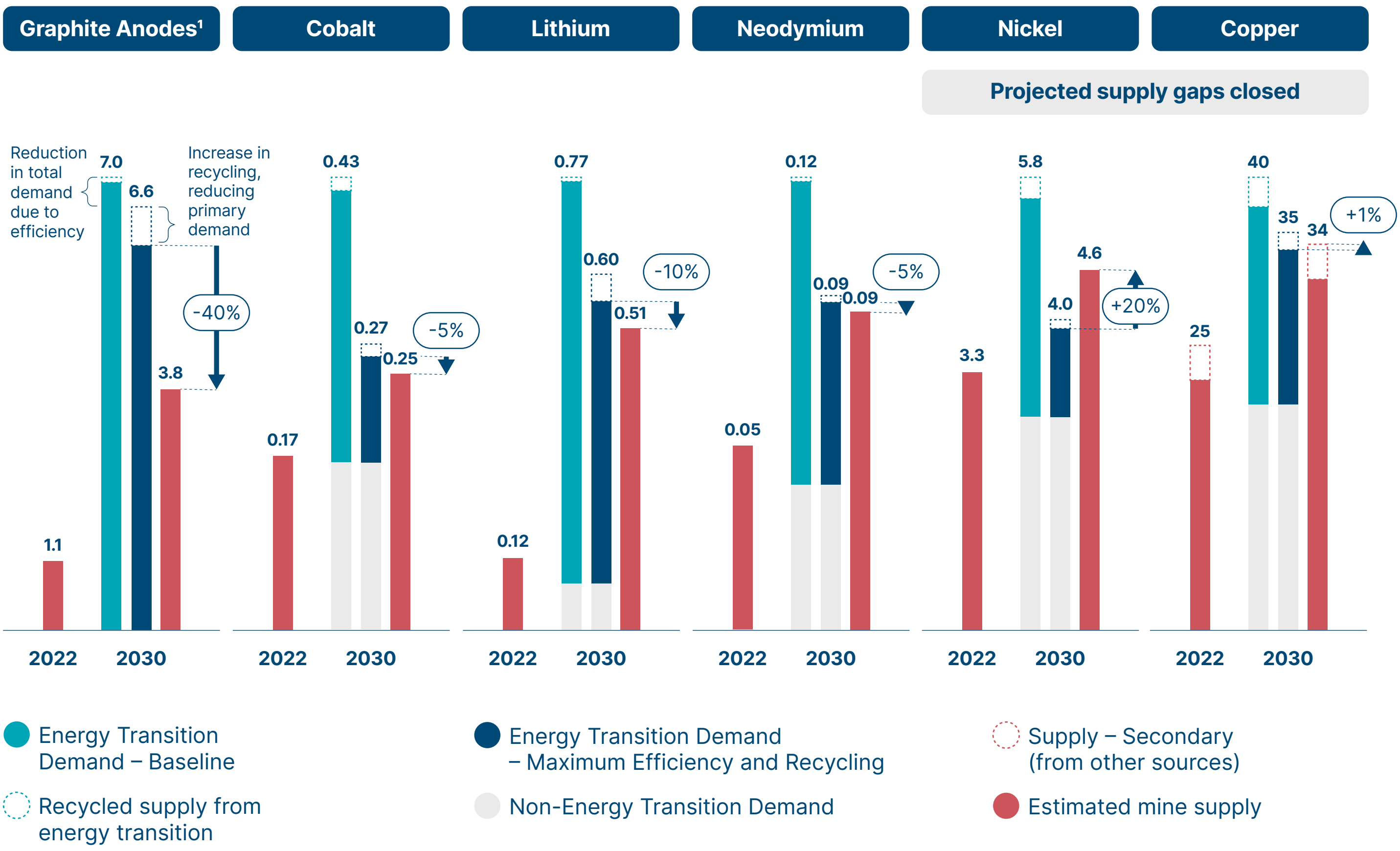
- For **cobalt**, there remain some uncertainties around future supply from the DRC, which has led to downward revisions in supply projections over the past year.[78] However, there is also strong potential supply expansion from Indonesia which could help close supply gaps further, and there is strong potential to reduce future demand by shifting to low-cobalt and cobalt-free battery chemistries – potentially going even further than illustrated here.[79]

- For **lithium**, substitution and demand reduction (from e.g., shifting to smaller batteries and the growth of sodium-ion (Na-ion) chemistries) beyond the levels in the Maximum Efficiency and Recycling scenario will be challenging. Existing mined supply pipelines will need to expand even further than current levels of up to 510 kt per annum by 2030,[80] with a greater number of projects needing to reach final investment decisions in the coming years. There could also be shortages of refined lithium hydroxide/carbonate [Box F].

EXHIBIT 2.19

Strong action on innovation, efficiency and recycling together can close supply gaps entirely for nickel and copper – but risks remain for several energy transition metals

Annual demand and supply in 2030 (Baseline Decarbonisation vs. Maximum Efficiency and Recycling scenarios)
Million metric tonnes



NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The Maximum Efficiency and Recycling scenario assumes accelerated progress in material and technology efficiency, and recycling clean energy technologies, thereby reducing requirements for primary materials. ¹ Supply only shown for natural graphite – it is likely that synthetic graphite could close most of the remaining supply gap.

SOURCE FOR ENERGY TRANSITION DEMAND: SYSTEMIQ analysis for the ETC.

SOURCE FOR NON-ENERGY TRANSITION DEMAND: Copper – BNEF (2022), *Global copper outlook*; Nickel – BNEF (2023), *Transition metals outlook*, Lithium, Cobalt, Neodymium – IEA (2021), *The role of critical minerals in clean energy transitions.*

SOURCE FOR PRIMARY SUPPLY: Copper, Nickel – BNEF (2023), *Transition metals outlook*, and assuming recycled copper from non-energy transition sources is 10% of primary supply; Graphite Anodes, Lithium, Cobalt – BNEF (2022), *2H Battery metals outlook*; Neodymium – estimated assuming continued CAGR in rare earth oxide production from 2010–21, through to 2030, with neodymium making up 17% of total supply.

78 BNEF (2022), *2H Battery metals outlook.*
79 Mining.com (2023), *Indonesia emerges as a cobalt powerhouse amid surge in demand.*
80 BNEF (2022), *2H Battery metals outlook.*

BOX F: Supply of refined vs. mined materials

This chapter has discussed end-use material requirements for clean energy technologies and compared them to expected supply of the relevant materials. Typically some amount of processing and/or refining is required to go from mined products to end-use materials. For example:

- **Steel:** In most cases, iron ore is mined and converted into pig iron in a blast furnace (in some cases, sponge iron is produced); there are then various stages of primary and secondary steelmaking, where impurities are removed from the iron and other elements are added to create steel of the desired composition. Typically, two tonnes of iron ore are needed to produce or one tonne of iron or steel. In this report we compare demand and supply for steel, not iron ore.

- **Aluminium:** Bauxite is mined; this is then refined into alumina (Al_2O_3), which is then smelted to produce aluminium. Typically, four tonnes of bauxite contain two tonnes of alumina, needed to produce one tonne of aluminium. In this report we compare demand and supply of aluminium, not bauxite.

- **Lithium:** Lithium can be extracted from brines or mined in hard rock ores. Depending on the extraction method, various stages of treatment and purification are carried out, with lithium refineries creating very high-purity lithium hydroxide or lithium carbonate for use in batteries. When mined from hard rock such as spodumene, around 170 tonnes of spodumene are needed to produce one tonne of lithium, and lithium carbonate contains around 19% pure lithium. In this report we compare demand of pure lithium contained in end-products (batteries) with mined supply of lithium.

- **Nickel or Cobalt:** Both nickel and cobalt are mined in as part of ores, with cobalt being co-produced alongside either copper or nickel. Application of both metals in steel alloys can make use of their metallic forms, but both materials need to be refined into high-purity cobalt/nickel sulphate to then be used in battery cathodes. In this report we compare demand of pure nickel/cobalt contained in end-products (batteries, wind turbines) with mined supply of nickel/cobalt.

There are no concerns around intermediate supply for e.g., steel or aluminium, where capacity is significant and the energy transition will drive a small share of demand. However, there are concerns that capacity for refined supply of both lithium carbonate/hydroxide and nickel sulphate could, on top of mined supply, also be insufficient to meet rapidly growing demand from batteries [Exhibit 2.20].

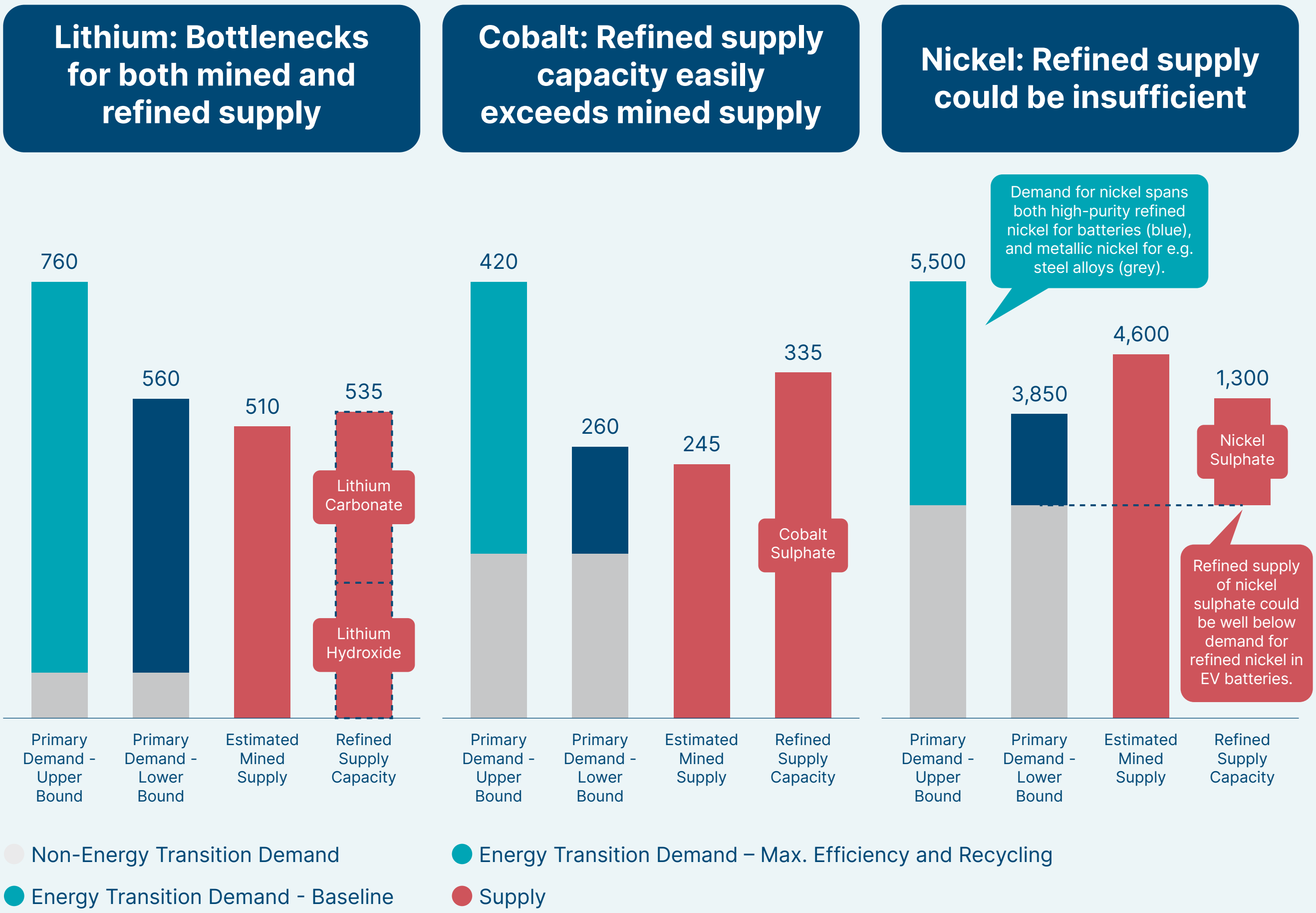
However, the much faster timescales involved in expanding refining capacity [discussed below, see Exhibit 3.4] mean that closing supply gaps for refined materials should be more feasible than gaps in mined supply.

EXHIBIT 2.20

Global capacity to produce refined, high-purity nickel could be a concern beyond primary mined supply; for lithium and cobalt bottlenecks are more likely at mine site

Mined vs. refined supply for key battery materials in 2030

Thousand metric tonnes of contained metal



NOTE: the ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The Maximum Efficiency and Recycling scenario assumes accelerated progress in material and technology efficiency, and recycling clean energy technologies, thereby reducing requirements for primary materials.

SOURCE FOR ENERGY TRANSITION DEMAND: SYSTEMIQ analysis for the ETC.
SOURCE FOR NON-ENERGY TRANSITION DEMAND: Nickel – BNEF (2023), *Transition metals outlook*, Lithium, Cobalt – IEA (2021), *The role of critical minerals in clean energy transitions.*
SOURCE FOR PRIMARY SUPPLY: Nickel – BNEF (2023), *Transition metals outlook*; Lithium, Cobalt – BNEF (2022), *2H Battery metals outlook.*
SOURCE FOR REFINED SUPPLY: BNEF (2022), *2H Battery metals outlook*, for lithium carbonate/hydroxide, cobalt sulphate, and nickel sulphate.

2.4.3 The supply scale-up challenge

Even with Maximum Efficiency and Recycling, there will be a gap between 2030 demand and currently planned supply for some materials, and if Maximum Efficiency and Recycling is not achieved, these gaps will be larger and more widespread. Significant increases in primary supply are therefore essential – the energy transition will require an expansion in metals mining.

Together, the analysis suggests that six key materials pose the greatest risks to the energy transition because of possible shortages of supply [Exhibit 2.21]:

- **Copper:** Mined output would need to rise from around 22 Mt up to at least 30 Mt in 2030. There are a range of projects that have completed earlier development stages and could begin production soon (e.g., La Granja, Resolution) but more are likely to be required.[81] Achieving such an increase will be challenging due to: long timescales for mines to come online, declining production from existing mines, declining ore grades, and disrupted supply from drought and local unrest in South America.[82] Further risks exist due to the widespread need for copper, which means that strong action on efficiency and recycling would need to take place across all clean energy sectors in order to have the significant impacts in our Maximum Efficiency and Recycling scenario. However, there may also be further potential for thrifting, efficiency and expanded recycled supply from non-energy transition sectors – reducing potential supply gaps.

- **Lithium:** Mined output would need to increase from 120 kt up to potentially over 750 kt at most in 2030. Current supply forecasts reach 510 kt,[83] so a further expansion beyond what is currently planned would be required – likely from both hard rock mining in Australia and China, from brines in South America, and maybe new direct lithium extraction approaches. New mining projects have tended to begin production faster than other commodities,[84] raising some hope that this expansion can take place rapidly. Supply of high-purity refined lithium carbonate/hydroxide could also be a concern [Box F].

- **Nickel:** Mined output would need to increase from 3.3 Mt to at least 3.5 Mt by 2030, but potentially up to over 5 Mt. Such an increase should be feasible, especially given the rapid expansion in supply from Indonesia in recent years. There could also be potential to shift demand away from the steel sector, easing potential supply constraints. However, supply of higher quality refined class 1 nickel, and battery-grade nickel sulphate, could be challenging [Box F].[85]

- **Cobalt:** Supply may only need to expand slightly, from 220 kt up to 260 kt, although there is a wide range of potential demand in 2030. Most future supply would come from DRC, which poses risks due to ongoing disruptions in eastern regions, although additional supply may also come from Australia, Canada and Indonesia.

- **Graphite:** Supply of natural graphite may need to expand from 1.1 Mt up to over 4 Mt. Most existing supply of natural graphite comes from China, but there are a large number of new projects planned across the USA and East Africa.[86] However, there is also strong potential to expand synthetic graphite production quite rapidly, helping to close the supply gaps outlined here – and providing some uncertainty around the scale of expansion required for natural graphite.

- **Neodymium:** Supply of neodymium may need to expand from current levels of around 50 kt up to 90 kt in 2030. This should be feasible, with large expansions in supply expected in China (the largest current supplier), as well as Myanmar, Australia and the USA.

For nickel, neodymium, cobalt and graphite, there is both scope for a significant increase in supply, and also for demand to shift away from these materials, incentivised by high prices. However, in the case of copper and lithium, there is a real risk that rapid growth in demand outpaces projected increases in supply – which would lead to tight markets and high prices through to 2030.

81 See e.g., BNEF (2022), *Global copper outlook 2022-40;* S&P Global (2022), *The future of copper.*
82 Ibid.
83 BNEF (2022), *2H Battery metals outlook.*
84 IEA (2023), *Energy technology perspectives;* IEA (2021), *The role of critical minerals in clean energy transitions.*
85 BNEF (2022), *2H Battery metals outlook.*
86 S&P Global (2022), *Feature: More projects needed globally to combat future graphite deficit.*

EXHIBIT 2.21

Market tightness is likely through to 2030 for many materials; Lithium poses biggest challenge for scale-up; Strong action on efficiency and recycling can reduce risks

- Low risk
- Low-Mid risk
- Mid-High risk
- High risk

Material	Baseline Decarbonisation: Short-term scale-up risk	Baseline Decarbonisation: Long-term scale-up risk	High Efficiency and Recycling: Short-term scale-up risk	High Efficiency and Recycling: Long-term scale-up risk	Key Considerations
Aluminium	Low risk	Low risk	Low risk	Low risk	• Expansion in demand and supply through to 2030 is in line with expansion in last decade.
Cobalt	High risk	Mid-High risk	Low-Mid risk	Low-Mid risk	• Required supply expansion is large, uncertainty over supply from DRC (supplies ~70% of market). • Demand mitigation requires fast shift away from cobalt-rich batteries – seen as plausible.
Copper	High risk	Mid-High risk	Mid-High risk	Mid-High risk	• Innovation levers have less impact due to widespread need for copper – hard to substitute away demand, but potential to expand role of recycling from energy technologies and non-energy sectors. • Very long timescales for new projects to come online (up to 20 years), increasing existing pipeline is challenging.
Graphite Anodes	High risk	Low-Mid risk	Low-Mid risk	Low risk	• Very large short-term ramp up due to BEVs, and competition with electrodes for steel as sector decarbonises. • Synthetic graphite production can ramp up quickly to close supply gaps, but requires fossil fuel inputs.
Lithium	High risk	High risk	High risk	Low-Mid risk	• Very large demand rise due to BEVs; lithium is very difficult to substitute (Na-ion an option over long-term). • Large supply expansion required beyond existing pipeline but new projects have begun production faster than for other commodities, new mining technologies in development.
Neodymium (REEs)	High risk	Mid-High risk	Low-Mid risk	Low risk	• Large demand rise from BEVs and wind turbines, but large reductions in material intensity possible. • Supply expansion likely to be heavily concentrated in China, but supply growth also in USA, Australia, Myanmar.
Nickel	Mid-High risk	Mid-High risk	Low-Mid risk	Mid-High risk	• Production has expanded quickly in Indonesia in recent years, but Class 1 nickel supply is challenging. • Demand mitigation requires fast shift away from nickel-rich batteries. • Mid-stream supply gap for refined nickel sulphate is also a concern.
Palladium and Platinum	Low-Mid risk	Low-Mid risk	Low risk	Low risk	• Rise in demand from electrolysers and fuel cells is more than offset by falling demand from ICE catalysts. • Reducing requirements from electrolysers would need fast adoption of Alkaline/AEM electrolysers.
Polysilicon	Low risk	Low risk	Low risk	Low risk	• Production capacity responds to price signals and expands very quickly (1–2 years). • Large share of current polysilicon production plants will need replacing in coming years, but this is seen as feasible.
Silver	Mid-High risk	Mid-High risk	Mid-High risk	Mid-High risk	• Demand from solar PV makes up >10% of market, but long-term demand is from industry, jewellery, investments. • Potential to shift demand away from other sectors and/or increase silver recycling.
Steel	Low risk	Low risk	Low risk	Low risk	• Expansion over next decade is significantly less than during commodity super-cycle of early 2000s.
Uranium	Low-Mid risk	Low-Mid risk	Low risk	Low risk	• Demand is highly dependent on type of nuclear power plants being developed, and ability to recycle and re-use spent uranium nuclear fuel rods.

SOURCE: SYSTEMIQ analysis for the ETC.

NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The Maximum Efficiency and Recycling scenario assumes accelerated progress in material and technology efficiency, and recycling clean energy technologies/materials.

Production from individual mines will depend on a range of factors, with three key determinants being commodity prices,[87] costs of operations, and local exogenous factors such as drought or social unrest.[88] Expanding supply can come from a variety of sources, depending on the material:

- Investing in new greenfield projects to access new resources, potentially making use of new technologies and innovations.
- Increased production from existing mines through higher utilisation rates.
- Brownfield expansions on existing mine leases.
- Re-processing of tailings to extract previously un-economical resources or developing new technologies for extraction – as discussed in Chapter 3.

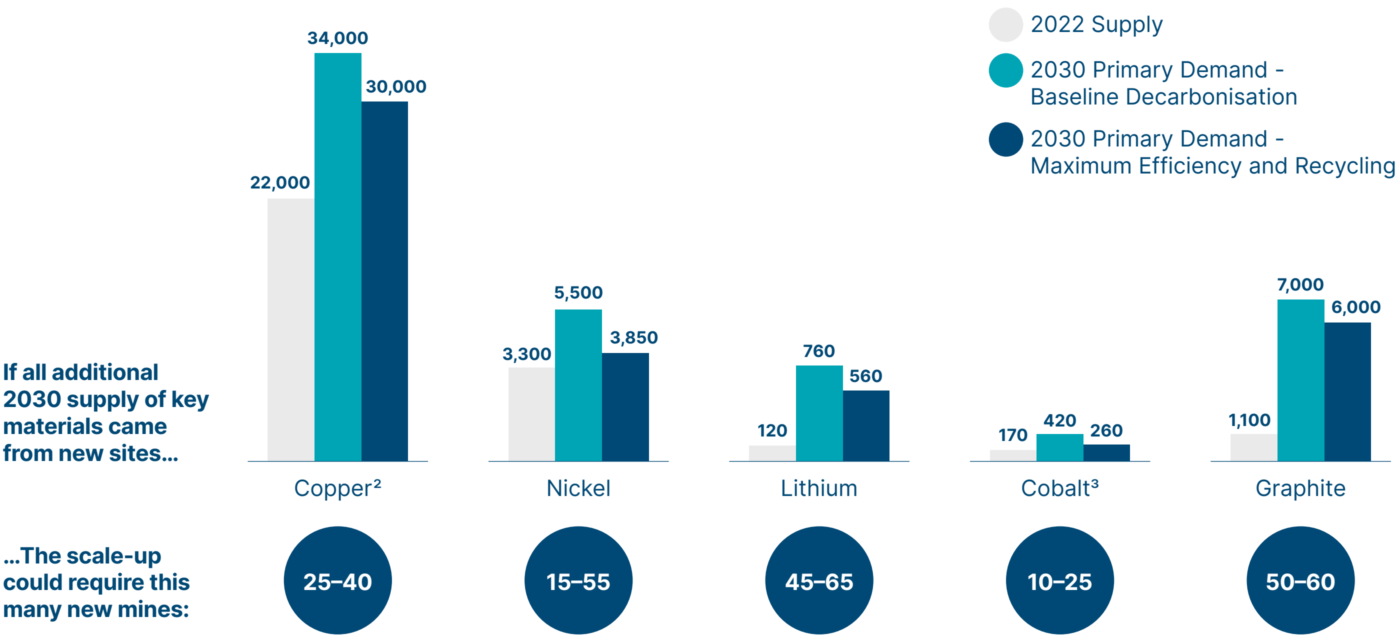
But if all additional supply were sourced from new mine projects, this would require about 145–245 new mines across the five key energy transition materials [Exhibit 2.22].[89]

Chapters 3 discusses the challenges involved in scaling supply and considers the implications of security of supply concerns. Chapter 4 then considers local environmental impacts arising from mining.

EXHIBIT 2.22

The scale-up in resource use could mean increased outputs equivalent to hundreds of additional mines by 2030

Required scale-up in demand and mines by 2030[1]
Thousand metric tonnes



[1] Estimated based on increase in primary demand to 2030 and average mine outputs of: Copper – 300 kt p.a.; Nickel – 40 kt p.a.; Lithium – 10 kt p.a.; Cobalt – 10 kt p.a.; Natural Graphite – 50 kt p.a. [2] Only mined supply shown for copper, to enable comparison with primary copper demand. [3] Cobalt is typically mined as a by-product of copper or nickel, so this figure is purely illustrative.

NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The Maximum Efficiency and Recycling scenario assumes accelerated progress in material and technology efficiency, and recycling clean energy technologies.

SOURCE: Systemiq analysis for the ETC.

87 See e.g., Chartered Institute of Procurement and Supply (2023), *Plummeting cobalt prices shows 'disconnect between supply chain planners and buyers'.*
88 See e.g., Financial Times (2023), *Peru unrest threatens copper supply.*
89 Estimated based on increase in primary demand to 2030 and average mine outputs of: Copper – 300 kt p.a.; Nickel – 40 kt p.a.; Lithium – 10 kt p.a.; Cobalt – 10 kt p.a.; Natural Graphite – 50 kt p.a.

2.5 Actions to improve efficiency and increase recycling

This chapter has outlined how technology and material efficiency and recycling can significantly alleviate pressure on the primary mined supply of key materials for the energy transition.

Developing this circular system relies on the private sector achieving six key outcomes, as set out in Exhibit 2.23. Doing so requires businesses to invest in:

- **Infrastructure:** investment is required in both the physical (e.g., recycling plants, manufacturing equipment) and digital (e.g., online platforms and software to improve production efficiencies, track product life cycles and end-of-life management) infrastructure.
- **Logistics:** developing the end-of-life collection system and transport and storage network required to access primary supply and distribute secondary supply.
- **R&D:** innovation is required to reach new potential efficiencies and to improve the quality and lower the cost of recycling processes.

EXHIBIT 2.23

Key outcomes of investments in technology and materials efficiency and recycling

Technology and materials efficiency	Recycling
Improving technical and operating efficiencies of technologies: for example, improved battery energy density, higher solar panel and electrolyser efficiency, improved siting and management of wind farms.	**Reducing scrappage and waste during production:** this helps decrease the volume of raw materials required to make an end-product.
Reducing or substituting material content: this has already been seen in the falling silicon and silver content of solar panels or expected reductions in PGM use in electrolysers.	**Improving end-of-life management and collection:** to avoid clean energy technologies and their embedded valuable raw materials from being sent to landfill.
Transition to less materials-intensive technologies: shifting away from cobalt-rich battery chemistries or moving from Proton Exchange Membrane (PEM) to Alkaline electrolysers.	**Increasing recycling quality and yield:** to increase the amount and quality of materials recovered through end-of-life recycling processes.

Developing the scale of the circular system required will not happen without well-designed real economy polices and regulations, which incentivise the private sector to make such investments, accelerate progress and overcome key barriers – but there are key differences in the extent of policy action required:

- **Technology and materials efficiency:** these improvements will largely be driven by prices and competition in the private sector. Companies constantly seek to lower costs (e.g., by reducing material intensity) and respond to market signals such as supply shortages and high prices for certain material inputs. However, there is a role for policymakers to accelerate these improvements in certain cases and to support with research and development.

- **Recycling:** realising the potential for significantly greater recycling will require a larger role for policymakers to overcome specific challenges and barriers to investment by playing a coordination and market orientation role.

This section discusses challenges and actions to overcome these.

2.5.1 Challenges to efficiency and recycling improvements

There are currently a number of challenges which prevent the private sector from driving fast enough progress – these are most prevalent with regards to recycling.

The main cross-cutting challenge for both efficiency and recycling is the uncertainty regarding the pace and scale of the transition and therefore demand for materials for clean energy technologies. This uncertainty, or in some cases, low confidence, reflects varying or lacking ambition in government commitments and an absence of supporting policies. For example, many developed countries have set targets for the phase out of ICE cars, but these are not supported by credible policies to scale-up charging infrastructure or develop sufficient battery supply chains. This reduces incentives to invest in efficiency and recycling, as the private sector does not place a high likelihood on supply gaps materialising.

For efficiency improvements, other challenges relate to financing accelerated research and development, coordinating this research across the value chain, and de-risking new solutions and first-of-a-kind projects to deploy these at scale. In addition, commodity markets are not perfect, with often volatile and unpredictable shifts in supply and prices (see Chapter 3.1) which dilute market signals for investment in efficiency.

For recycling improvements, the challenges are more prohibitive. These vary across different technologies and materials, but include three major themes:

- **Complex and fragmented value chains**, with a lack of coordination between the various players (e.g., mining companies, manufacturers, retailers, consumers, and waste/recycling companies).
    - This can dilute market signals which incentivise investment in recycling. For example, in the case of copper, its widespread use across multiple sectors (e.g., power, consumer electronics, transport and construction) can create challenges for coordination and collection of scrap.
    - This can also include fragmented trade around secondary goods, scrap, and waste, with export restrictions or imbalances in environmental and social regulations leading to uneven playing fields.[90]
    - A key distinction is between systems dominated by business-to-business interactions, where often it is easier to align incentives to encourage recycling, and systems that rely on consumers for crucial steps (i.e. return of vehicles or products at end of life).[91]
- **The complexity of the recycling process** for many clean energy technologies, due to the nature of their material composition and the wide variety of different designs. Key challenges include:
    - EV battery packs vary considerably in design, including different chemistries and nickel and cobalt content, and ease of disassembly. This adds complexity and cost to the recycling process. Further, the varying materials content of different battery chemistries, and the divergent approaches of hydrometallurgy and pyrometallurgy can lead to a wide range of break-even costs for recycling of different battery chemistries.[92]

90 See e.g., Chatham House (2022), *The role of international trade in realizing an inclusive circular economy.*
91 Hagelüken and Goldmann (2022), *Recycling and circular economy – towards a closed loop for metals in emerging clean technologies.*
92 Lander et al. (2021), *Financial viability of electric vehicle lithium-ion battery recycling.*

    - Wind turbine blades are made from mostly composites, such as carbon fibre and resins, making separation in the recycling process difficult and expensive.[93]

    - Most clean energy technologies are developing rapidly, with continuous innovation to improve design (and, in many cases, reduce material content). This creates a challenge for recyclers to adapt quickly enough to new technology developments whilst still turning a profit.

- In some cases, recycling is simply **not currently cost-effective**. In addition to the factors above, this can also reflect:

    - A lack of volume in the initial stages of the energy transition – as discussed in Chapter 2.2, it will take time for today's clean energy technologies to reach their end of life and enter into a secondary market. Low volumes mean higher costs, but these will fall over time due to economies of scale and learning effects.

    - Recoverable materials may have low resale values, which do not offset the costs of recycling. For example, in the case of solar panels, silver accounts for half of the material value but represents less than 1% of the module mass.[94]

2.5.2 Recommendations to drive investment in efficiency and recycling

Policymakers and regulators must start by creating confidence that demand for clean energy technologies and their key inputs will materialise. The investments in recycling and efficiency will only be profitable if the private sector judges that the rapid growth in demand outlined in this Chapter is likely to occur. Policymakers can do that through well-designed real economy policies, such as clear targets for power sector decarbonisation and appropriate power market design; see Chapter 5 for more detail.

To overcome the more specific barriers discussed above, policymakers also need to:

- **Accelerate improvements in materials and technology efficiency** through targeted incentives and research and development.

- **Create economic incentives for scaling recycling** and re-use and the secondary supply of critical materials.

It is important to note that the aim is not necessarily to achieve a 100% recycled supply of all materials – this would be economically and energetically inefficient.[95] Instead, action should be focused on the most critical materials where expanding recycled supply can make sense, for example where:

- **Demand is rising very rapidly**, for example lithium for EV batteries.

- There are likely to be **mined supply shortages**, for example for lithium or copper.

- **Safe and sustainable end-of-life waste is a challenge**, for example disposing of materials or clean energy technologies that could be highly polluting if not landfilled appropriately (e.g., lead in solder used in solar panels).

- **Mining of primary supply has significant negative impacts**, for example, cobalt in the DRC or rare earth element mining in northern China.

93 Iberdrola (2021), *Wind blade recycling, a new challenge for wind energy.*
94 IRENA and IEA (2016), *End-of-Life Management: Solar Photovoltaic Panels Report.*
95 Wellmer and Hagelüken (2015), *The feedback control cycle of mineral supply, increase of raw material efficiency, and sustainable development.*

There are **five key actions**, outlined below along with the priority materials and technologies that these actions should target this decade:

Responsible actors: ● ◕ Leading actors; ◑ ◔ Supporting actors

① Increased investment in research and development, including public targets and prizes

Policymakers & regulators	Downstream value chain	Financial institutions
●	●	

Innovation is required to raise the ceiling for potential material and technology efficiency, and to improve the effectiveness and lower the cost of recycling processes.

Approaches to achieving this can include:

- **Financial incentives** for manufacturers and universities (e.g., tax breaks, targeted subsidies and grants for R&D).
- Developing **industrial and research clusters**.
- **Prizes and targets** from universities, research funders or philanthropists to drive innovation in a specific area.
- At the deployment stage, **public investment or advance market commitments** for the first large-scale projects, e.g. recycling plants or manufacturing for new technologies.

Key priorities for materials and technology efficiency:

- Increased investment and incentives to drive improvements in energy density and packing efficiency of EV batteries.
- Incentivising a faster shift to lithium-iron phosphate (LFP) batteries which use less nickel and cobalt.
- Rapid development and deployment of next-generation batteries, e.g., Na-ion, solid-state, Li-metal.
- Funding university-level research into next-generation solar PV, wind and electrolysers – to achieve the improvements outlined in Exhibit 2.7.

Key priorities for recycling:

- Driving R&D for better disassembly of battery packs and modules, and improved sorting technologies for electrode materials.
- Research into appropriate recyclable materials for wind turbine blades, or recycling approaches that enable the separation of composites.
- Driving higher quality of recycled material outputs – enabling secondary materials from clean energy technologies to be re-used in the same applications.

② Regulatory standards and mandates

Policymakers & regulators	Downstream value chain	Financial institutions
●	◑	

Introducing strong regulatory requirements on both domestically-produced and imported products can help accelerate and target progress on both efficiency and recycling.

Key priorities for materials and technology efficiency:

- **Materials efficiency standards** that set a gradually decreasing maximum material intensity level (e.g., on lithium content per kWh of battery capacity), akin to existing fuel efficiency standards in California.
- **Performance standards** for new clean energy technologies, e.g., for battery energy density, solar efficiency, electrolyser efficiency.

Key priorities for recycling:

- Regulations on the level of recycled content in end products, and on final recovery rates for materials at end of life.
- Strong regulations on the minimum environmental impacts associated with recycling – to avoid "leakage" of recycling processes to countries with lower standards.
- Bans on the use of landfill for particular technologies to incentivise recovery and recycling.
- Public targets e.g., for numbers of recycling plants or recycling capacity for EV batteries.

③ Create economic incentives for efficiency and recycling measures

Policymakers & regulators	Downstream value chain	Financial institutions
●	◑	

Policymakers can use a variety of fiscal tools to create a market for particular technologies with increased efficiency or high recycled materials content – helping overcome short-term cost barriers.

Key priorities across both materials and technology efficiency and recycling:

- **Public procurement or offtake agreements** to create early demand for cutting-edge technologies with lower materials intensity, or for large volumes of secondary supply of key materials.
  - For example, public procurement of end-of-life EV batteries for deployment as stationary grid storage, or for large-scale production of next-generation batteries.
- **Fiscal measures** such as:
  - Taxation of SUVs/oversize batteries over a certain weight to incentivise greater materials and performance efficiency.
  - VAT reductions for circular products and services can create economic incentives, including lower-carbon intensity products, remanufactured and refurbished technologies and spare parts, or products with high recycled content.
  - Fiscal policy can also be used to create disincentives for waste, for example, landfill disposal fees.
- **Carbon pricing** or other pricing of externalities can create further incentives for circular business models where the emissions of recycled materials are substantially lower than primary materials.
  - In exceptional cases, taxation on primary materials or outright subsidies for secondary materials could be considered (for example, if supply of primary copper were exceptionally tight). However, these might lead to perverse economic incentives around the use of existing materials in stock.[96]
- Targeted **subsidising of recycling processes** where it is not currently cost-effective to, reducing these over time as technologies are scaled up and learning effects lower costs.
  - For example, research suggests that an initial subsidy of around $18/panel could help get a recycling industry off the ground and to break even by the mid-2030s.[97]
  - Recycling of LFP batteries may require a subsidy of 5–20 $/kWh, depending on location and approach, to initially scale recycling [Exhibit 2.12].[98]

96 Soderholm and Ekvall (2020), *Metal markets and recycling policies: impacts and challenges.*
97 Walzberg, J., et al. (2021), *Role of the social factors in success of solar photovoltaic reuse and recycle programmes.*
98 Lander et al. (2021), *Financial viability of electric vehicle lithium-ion battery recycling.*

④ Incentivise optimisation for low life-cycle impacts of technologies, including end of life

Policymakers & regulators	Downstream value chain	Financial institutions
●	●	

Forward planning is needed today to design clean energy technologies for longer life, easy disassembly and recycling, and which minimise materials intensity. Regulation to reduce life-cycle impacts can help drive manufacturers to improve the materials intensity, technical efficiency, and recyclability of products.

Key priorities across both materials and technology efficiency and recycling:

- Regulation which mandates **reductions in embodied emissions** for clean energy technologies.
  - For example, the French government has introduced a "Simplified Carbon Assessment" that includes the life cycle carbon intensity of new solar PV farms in evaluating bids for new projects.[99]
- Considering well-designed regulation for **extended producer responsibility**, whereby manufacturers are responsible for a product in the post-consumer stage, to internalise costs associated with recycling or end-of-life management and reflect these in upfront consumer prices.
- Enabling discussions between manufacturers and recycling **companies to share best practices** and identify areas for improvement in design and collection.
- Developing **standards and guidance** on extending product lifetimes (e.g., identifying uses for second life batteries).
- Encouraging **standardisation and simplification** of key components in clean energy technologies, e.g., battery packs or EV chargers, to aid disassembly.

⑤ Improve data availability throughout the life cycle of technologies

Policymakers & regulators	Downstream value chain	Financial institutions
●	◑	

Measuring and monitoring information on embedded materials in clean energy technologies will enable optimal decisions in the design stages and at end of life. Key data points include:

- Material inputs and intensities (e.g., breakdowns across components, hazardous substances, primary vs secondary material).
- Repair and dismantling information.
- Dynamic information, for example, on battery whereabouts and product/component condition.

Key priorities across both materials efficiency and recycling:

- Establishing **frameworks and standardised databases for data collection**, reporting and sharing across companies and countries. International conferences, such as the UNFCCC's COP meetings or UNEP gatherings, could provide an opportunity to establish a global data governance framework.

99 Ultra Low-Carbon Solar Alliance (2021), *Reducing the carbon footprint of solar: the French model.*

- Regulation should be used to **enforce data collection, tracking and transparency**.
  - This includes measures to make relevant information commercially available, including ensuring data protection and encouraging collaborative data exchange between companies (e.g., initiate and provide funding for digital systems including product passports).
  - The ongoing development of a European battery passport is leading the way in driving a step-change in data transparency across the industry,[100] which could serve as a benchmark for implementation in other countries.
- **Standardisation of definitions and standards for secondary materials**, including how to classify the status of secondary content and quality standards for remanufactured products and recycled materials.
- Public-private collaborations to **understand and promote best practices** and set benchmarks.

These actions, whilst predominantly driven by policy, will require concerted collaboration with industry in specific areas such as driving R&D, collaborations to improve data sharing and availability, and creating smart incentives around life cycle optimisation.

One key risk that will need careful management as policies are developed, is the potential for strong trade-offs in certain cases between improving technology and materials efficiency and enabling increased recycling.

For example, shifting to LFP batteries can help significantly reduce demand for cobalt and nickel – reducing battery cost and the associated impacts from primary supply of these two materials. However, LFP batteries are currently much less economically profitable to recycle.[101] Similarly, efforts to improve battery energy density and packing could work against a desire to improve design-for-recycling and easy disassembly at end of life.

These challenges are far from insurmountable, but well-designed policy and potentially fiscal support will be needed in order to secure progress on both fronts simultaneously.

2.5.3 Ongoing policy developments to scale recycling in key regions

Measures to promote recycling, especially of EV batteries, have developed rapidly over the past few years:

- In **Europe**, the Critical Raw Materials Act includes a target for 15% of demand in 2030 for certain metals to be met by recycled supply,[102] and proposals for the European Battery Regulation include targets for collection of batteries at end of life (73% in 2030) and recovery rates for specific materials (e.g., 80% of lithium in 2030).[103]
- In **China**, the Ministry of Industry and Information Technology has outlined requirements for end of life for batteries through a series of directives in recent years, aiming to expand re-use and recycling.[104] These include pilot projects for battery life cycle traceability, and adopting an end-of-life hierarchy where batteries first are re-used in lower-capability applications (e.g., stationary storage or light electric vehicles) before eventually being recycled.
- The Inflation Reduction Act, passed in the **USA** in 2022, includes EV tax credits with domestic production requirements that also include materials recycled in North America. It further includes tax credits for energy projects associated with "industrial or manufacturing facilities for production or recycling" – providing some incentives for scaling recycling capacity.[105] However, outright targets for collection at end of life or recycling recovery rates are missing from the act.

These measures provide a strong basis for optimism in the case of battery materials, potentially bringing future trajectories closer to the High Recycling scenario outlined here, and other clean energy sectors should aim to follow suit in order to develop more circular clean energy supply chains.

100 Batterypass (2023), *About.*
101 Lander et al. (2021), *Financial viability of electric vehicle lithium-ion battery recycling.*
102 EU Commission (2023), *Critical raw materials act.*
103 EU Commission (2022), *Green Deal: EU agrees new law on more sustainable and circular batteries to support EU's energy transition and competitive industry.*
104 Electrive (2022), *Battery reuse & recycling expand to scale in China.*
105 Bipartisan Policy Center (2022), *Inflation Reduction Act Summary: Energy and Climate Provisions.*

Ensuring adequate and secure supply

Scaling primary supply will be crucial to meeting rapidly growing demand. To achieve this, four key challenges need to be overcome: difficulties projecting future demand, long mining timescales, a lack of investment, and challenges in increasing current mining output. Concerted action from policymakers, miners and investors will be needed in order to create certainty of future demand, accelerate mine development timescales, increase current capital expenditure from $45bn each year up to $70bn through to 2030, and increase mining productivity.

Chapter 2 described how action to drive technology and materials efficiency, and to maximise recycling, can help alleviate pressure on primary demand and supply. But even with ambitious improvements in efficiency and recycling, the energy transition will still require a significant expansion in mining, especially over the next decade. This is most notable for copper, nickel, graphite, cobalt and lithium.

That expansion will be driven primarily by private investment in anticipation of future demand. But coordinated public policy and industry action can also play an important role in ensuring adequate supply, both globally and within specific regions or countries.

This chapter therefore explores the **challenges** which might prevent adequately fast supply expansion and the **actions** which can mitigate this risk. It covers in turn:

1. The primary role of inherently imperfect markets
2. Challenges to a smooth transition
3. Actions to overcome these challenges
4. Geographical concentration and security of supply concerns
5. Actions to build secure supply and the need for a balanced approach

3.1 The primary role of imperfect markets

The supply gaps identified in Chapter 2 will, in many cases, be closed because private business will invest to build supply in anticipation of future high demand and/or prices. This will inevitably be an imperfect, and at times highly volatile, process; commodity markets have always been characterised by periods of over- and under- investment, and price surges and collapses, long before anyone talked about the need for the transition to a net-zero economy.[106]

This process can be seen at work in two key markets over last few years:

- **Polysilicon**, where the last three years have seen [Exhibit 3.1]:
  - A fivefold increase in prices between 2021–22, which resulted from a surge in demand combined with COVID19-induced supply shortages.
  - A dramatic increase in capacity in response to these high prices, which was possible since polysilicon plants can be built in only 1–2 years.
  - A resultant emerging supply glut and price collapse.

106 See e.g., World Bank (2022), *Commodity price cycles in three charts.*

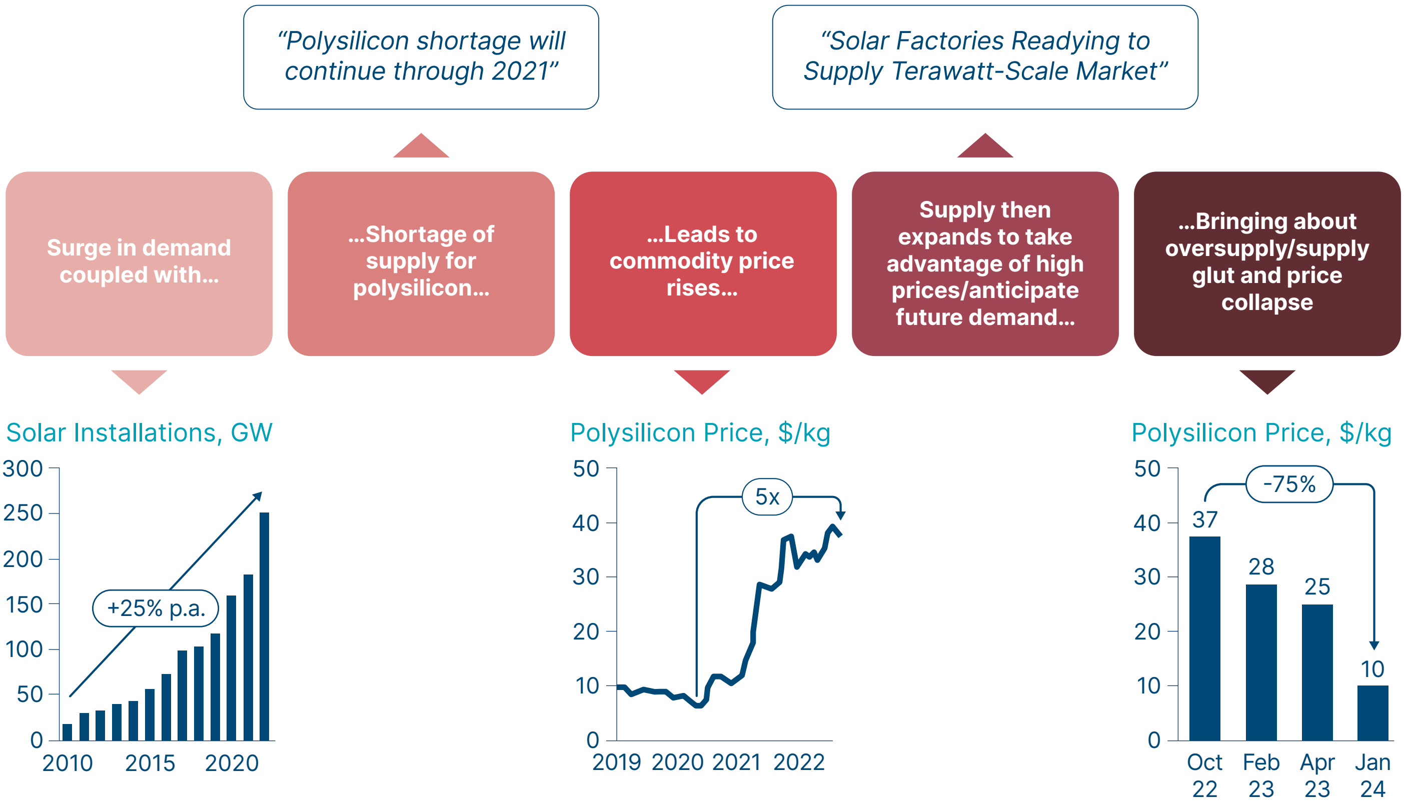
Similar polysilicon price volatility, resulting in fluctuations in solar panel prices around a strongly declining long-term trend, will almost certainly be seen in the future, but will not create any serious impediment to the energy transition.

- **Lithium**, where awareness that EV demand was taking off led to a dramatic surge in lithium carbonate prices between 2020–22 [Exhibit 3.2].
  - Alongside price spikes for nickel and cobalt, together these led to a 7% increase in battery prices in 2022.[107]
  - However, this year, slightly reduced expectations of short-term demand, together with significant new supply, have led to a fall in prices of nearly 70% since the peak in 2022.

Fluctuations in prices are, to a degree, inevitable over the next decade and beyond, and no public policy or improved industry coordination can entirely eliminate them. But analysis of the factors which drive this behaviour can suggest actions to at least mitigate some volatility and to reduce the risk that supply constraints could seriously slow the pace of the energy transition.

EXHIBIT 3.1

The most recent polysilicon price cycle lasted less than two years and had a minimal impact on solar prices and deployment

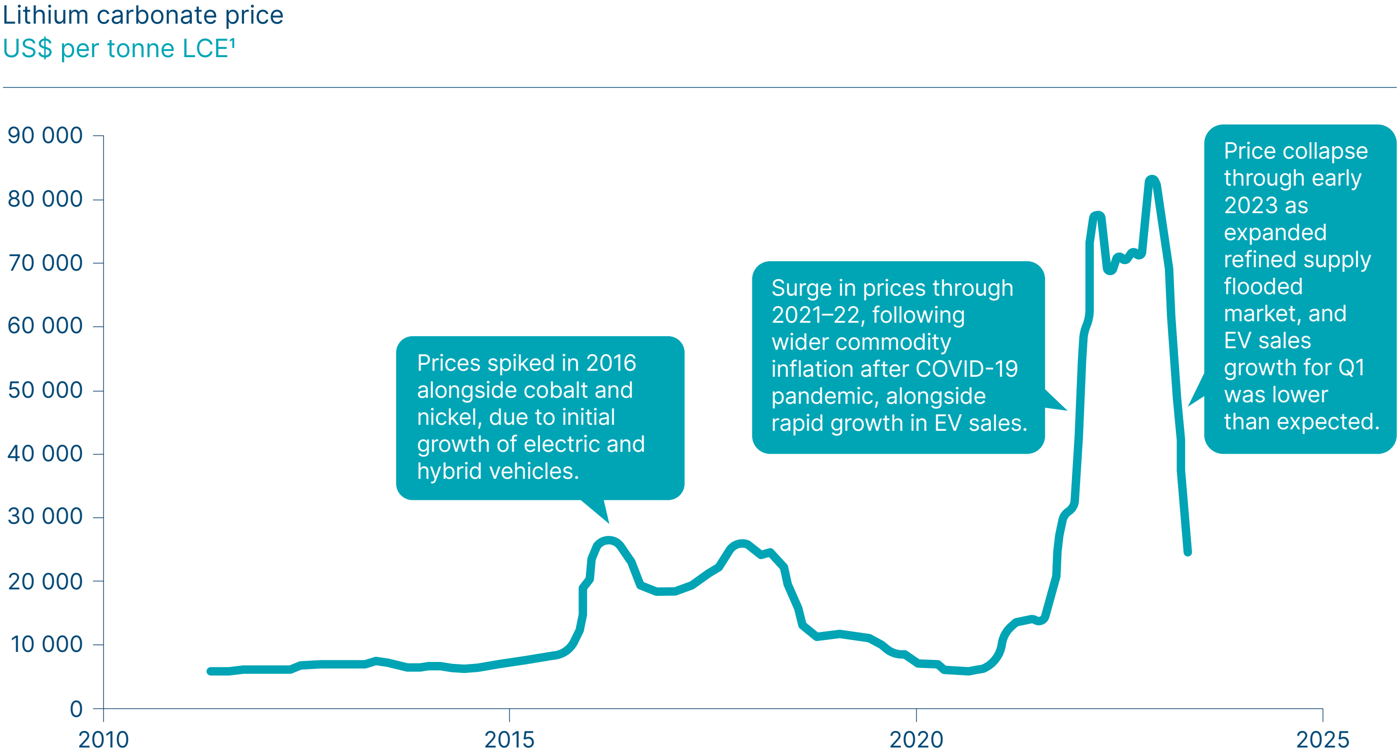


SOURCE: BNEF (2023), *Solar Spot Price Index*; BNEF (2023), *1Q Global PV market outlook*; PV Magazine (2021), *Polysilicon shortage will continue through 2021*; BNEF (2022), *Solar factories readying to supply terawatt-scale market.*

107 Prices rose from $141/kWh in 2021 to $151/kWh in 2022. BNEF (2022), *Lithium-ion battery price survey.*

EXHIBIT 3.2

Lithium carbonate has seen multiple price cycles as the EV market has developed



NOTE: [1] LCE = Lithium carbonate equivalent. Lithium carbonate is the commonly traded form of lithium product (alongside lithium hydroxide), and is a key refined material needed to produce battery cathodes. LCE contains approximately 19% pure lithium content. Price is for China lithium carbonate 99.5% DEL contract.

SOURCE: BNEF (2023), *Interactive data tool – Battery metal prices*; BNEF (April 2023), *Battery metals monthly.*

3.2 Challenges to a smooth scale-up in primary supply

Four challenges increase the risk of a volatile and insufficiently rapid transition:

- Inherent difficulties in projecting demand growth.
- Lengthy timelines to develop new mines.
- Inadequate investment in response to the first two factors.
- Falling mine productivity and challenges to increasing mine output.

3.2.1 Inherent difficulties in projecting demand growth

As Chapter 2 described, it is certain that demand for multiple minerals will increase very significantly over the next 10 years. But the precise scale and timing of demand growth for any one mineral is still highly uncertain.

This would be true even if the overall pace of the energy transition were fairly predictable. All four of the demand scenarios presented in Chapter 2 assumed the same pace of development of renewable electricity generation, green hydrogen production, and EV sales, but with varying assumptions relating to technical efficiency, specific material choices and the extent of recycling. This is illustrated in the very large variation in potential demand in 2030 in Exhibit 2.19, with lithium demand potentially 20% lower than in the Baseline Decarbonisation scenario, and nickel potentially 30% lower if maximum technical efficiency and recycling could be achieved.

In reality however, the range of possible results is increased still further by uncertainties about the overall pace of the energy transition,[108] with projections for volumes of relevant activity varying significantly over time and between different expert groups. Thus for instance:

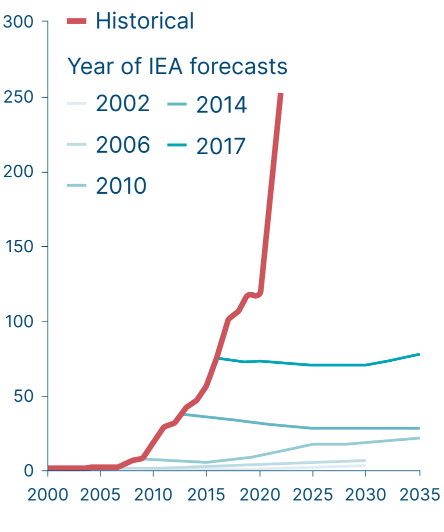
- IEA projections for total growth in solar PV have dramatically increased in recent years, with major revisions sometimes made from one year to the next [Exhibit 3.3, LHS].
- A similar pattern is now being seen with electric vehicles, where the market is at an earlier stage in its deployment journey: forecasts of EV sales keep getting revised upwards [Exhibit 3.3, Centre].
- Published projections for the total global number of passenger EV sales in 2030 also vary significantly depending on scenarios, ranging from 33 million up to 72 million [Exhibit 3.3, RHS].
- New unanticipated policy developments, such as the US Inflation Reduction Act, can produce large and sudden movements in reasonable anticipation of future demand growth for EVs, wind turbines, solar panels, electric grid equipment, or electrolysers.

Importantly, here innovation can play a role in driving uncertainty in either direction: innovation can rapidly reduce expected demand for certain materials but also lead to sharp increases in demand for new alternatives – as is currently happening for cobalt and nickel, where projected demand for the former has fallen sharply [Exhibit 2.10] but at the expense of faster growth in nickel demand.

EXHIBIT 3.3

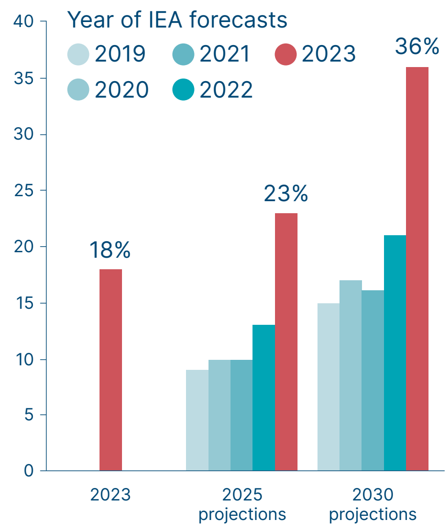
Clean energy deployment is hard to predict, making future material demand forecasts and investment decisions uncertain

Annual solar PV installations compared to IEA forecasts
GW



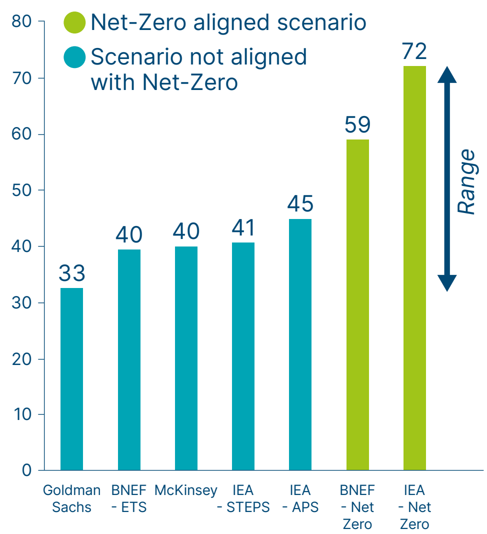
IEA forecasts have consistently underestimated the pace of solar PV installations.

Forecasts of electric vehicle's share of passenger vehicle sales
% of total sales



Expectations of EV sales this year are higher than BNEF's projections for 2030 made only two years ago.

Forecasts of passenger electric vehicle sales in 2030
Million vehicles



Forecasts of passenger EVs vary considerably.

NOTES: ETS = Economic Transition Scenario; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

SOURCE: Auke Hoekstra/IEA World Energy Outlooks; Hoekstra et al. (2017), *Creating Agent-Based Energy Transition Management Models That Can Uncover Profitable Pathways to Climate Change Mitigation*; BNEF (2023), *Interactive data tool – Global installed capacity*; Hannah Ritchie/IEA Electric Vehicle Outlooks; BNEF (2022), *Long-term electric vehicle outlook*; Goldman Sachs (2023), *The ecosystem of electric vehicles*; IEA (2023), *Global EV outlook*; McKinsey & Co. (2023), *What is an EV?*

108 See e.g., the ETC's analyses on progress: ETC (2021), *Keeping 1.5°C alive*; ETC (2022), *Degree of urgency*.

3.2.2 Long lead times for mine development

Rapid changes in expected demand and short-term price movements can sometimes produce rapid supply responses – as Exhibit 3.1 illustrated for polysilicon. Some key elements in supply chains – for instance, solar PV manufacturing, refining capacity, and EV battery plants, can be built relatively quickly.

But timescales for the development of mines are usually much longer, though they vary depending on material [Exhibit 3.4]:

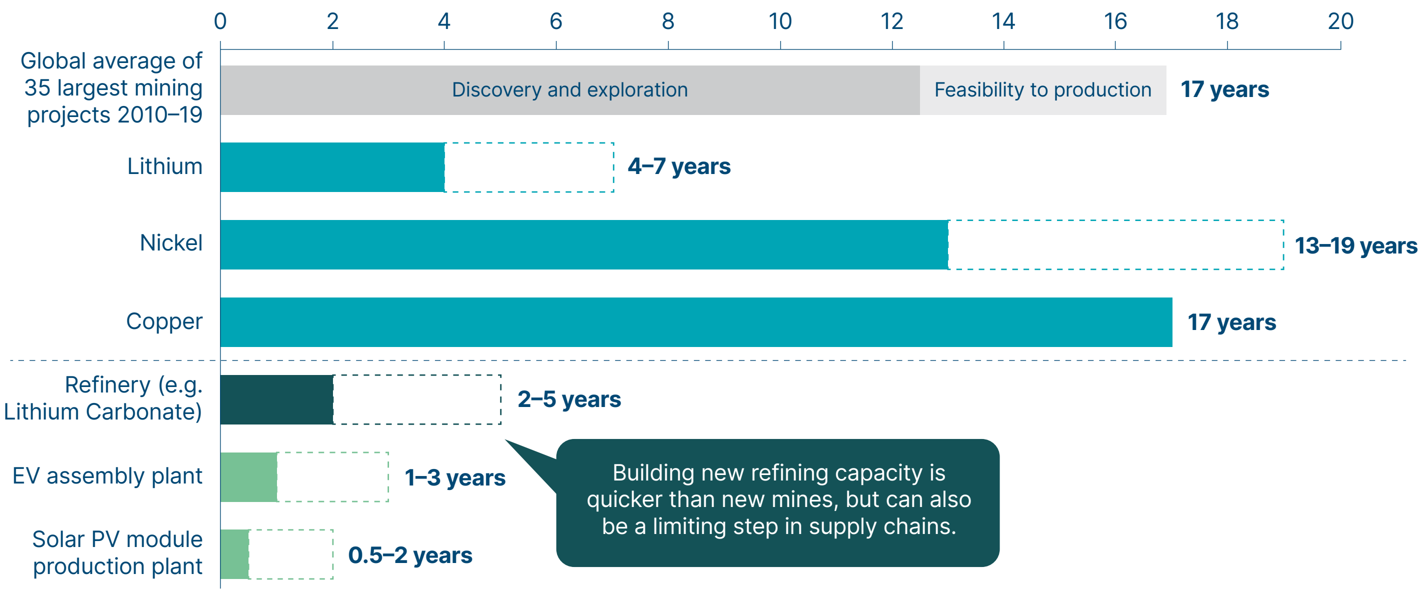
- **Copper and nickel** projects historically have required at least 7–8 years to go from feasibility to production, and once earlier exploration and development stages are included, can take over 20 years in certain cases.[109]
  - However, recent new nickel projects in Indonesia have been granted very rapid approval and permits, and have been able to begin production much more quickly.[110]
  - Timescales to go from discovery to production have also been falling for copper,[111] therefore there might be scope for a large number of projects that have already carried out exploration to carry out feasibility and construction quite quickly, ramping up production within the next decade.[112]
  - Brownfield project developments can also be developed more quickly: Goldman Sachs estimate brownfield copper projects have lead times that are 4–6 years faster than for new greenfield projects.[113]
- **Lithium** projects can often be developed over a faster 4–7 years, in part due to the smaller scale of typical operations.[114]

EXHIBIT 3.4

Timescales for mining projects are long, reducing the ability of the sector to respond to supply shortages and high prices

Average observed lead time¹

Years



¹ For mining this includes discovery and exploration, and feasibility and construction through to production.

SOURCE: IEA (2021), *The role of critical minerals in clean energy transitions*; Petavratzi and Gunn (2022), *Decarbonising the automotive sector: a primary raw material perspective on targets and timescales*; IEA (2023), *Energy technology perspectives.*

109 Heijlen et al. (2021), *Assessing the adequacy of the global land-based mine development pipeline in the light of future high-demand scenarios: The case of the battery-metals nickel (Ni) and cobalt (Co)*; IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions.*

110 IEA (2023), *Energy Technology Perspectives;* Carnegie Endowment for International Peace (2023), *How Indonesia used Chinese industrial investment to turn nickel into the new gold.*

111 World Bank (2016), *From commodity discovery to production: Vulnerabilities and policies in LICs.*

112 Ibid.

113 Goldman Sachs (2021), *Copper is the new oil.*

114 IEA (2021), *The role of critical minerals in clean energy transitions.*

Across most projects, early stages of discovery and exploration take the longest, and obtaining permits and addressing legal challenges and environmental impact assessments can also delay projects [Exhibit 3.5].

Brownfield projects, i.e. expansions on existing mine leases, can occur much quicker as these make use of existing equipment, infrastructure, knowledge and capacity.

The longer the time scale involved, the greater the danger that the interaction between rapidly changing expectations of medium-term demand versus short-term fixed supply will generate extreme price volatility, and the danger of serious supply constraints.

EXHIBIT 3.5

Timescale for large new mining projects can be nearly 20 years; projects can often be constrained by slow planning and permitting

SOURCE: International Resource Panel (2020), *Mineral Resource Governance in the 21st Century*; Heijlen et al. (2021), *Assessing the adequacy of the global land-based mine development pipeline in the light of future high-demand scenarios: The case of the battery-metals nickel (Ni) and cobalt (Co)*; IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*; Global Arbitration Review (2021), *Construction in the Mining Sector*; Petavratzi and Gunn (2022), *Decarbonising the automotive sector: a primary raw material perspective on targets and timescales*; World Bank (2016), *From commodity discovery to production*; Roskill/EU Joint Research Centre (2021), *Study on future demand and supply security of nickel for electric vehicle batteries.*

3.2.3 Inadequate investment

[Exhibit 3.6] presents an estimate of the investments in mining, refining and recycling plants required to provide adequate supply of five key materials. Depending on the demand scenario, cumulative investment needs for cobalt, copper, graphite, lithium and nickel from 2021–50 could range from $1.1 trillion to $1.7 trillion, of which $480–750 billion relates to mining.[115]

Around three-quarters of this investment is needed in the next decade to support the large ramp up implied by all the demand scenarios presented in Chapter 2. Thereafter, investment needs, especially for mining, could fall off rapidly if technical efficiency trends are strong and maximum recycling is achieved.

115 Note that these sums include both business-as-usual investment and additional investment required to meet extra energy transition demand. Systemiq analysis for the ETC; see also IEA (2023), *Energy technology perspectives*; Benchmark Mineral Intelligence (2023), *Tesla's Master Plan may underestimate scale of mining investment*; Tesla (2023), *Master plan part 3.*

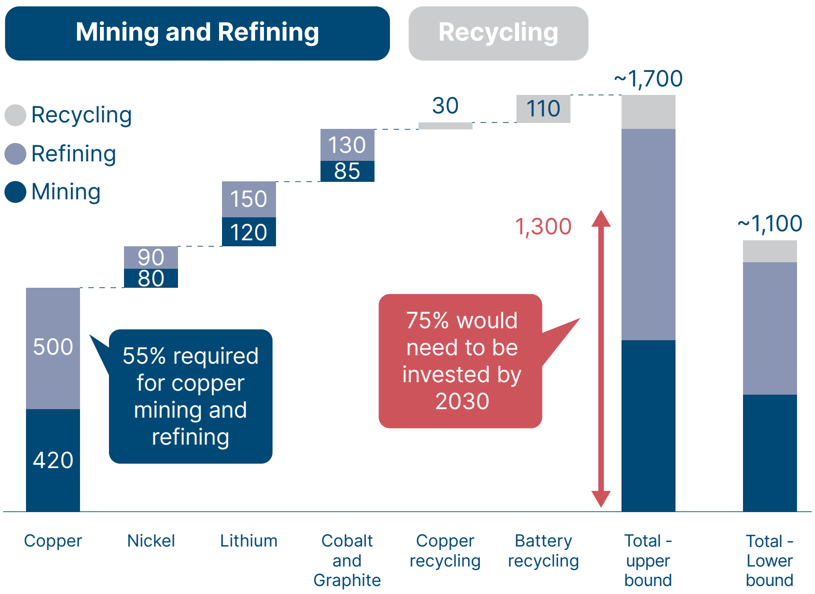
Relative to the next decade requirement, of around $70 billion each year [Exhibit 3.7], there is a capital investment gap of around $25 billion per annum from average levels of the last decade, with exploration investments for nonferrous[116] metals other than gold also low and not on a clear rising trend.[117] This compares to an annual average investment requirement of around $3.5 trillion each year identified by the ETC for the wider energy transition, within which some of these mining and refining investments would fall.[118]

This potentially inadequate investment, in particular around 2015 to 2017, reflected, in part, low commodity prices after the end of the pre-2008 "super-cycle".[119] This illustrates the danger that investment needed to meet long-term supply requirements can be curtailed by short-term price fluctuations and financing constraints.

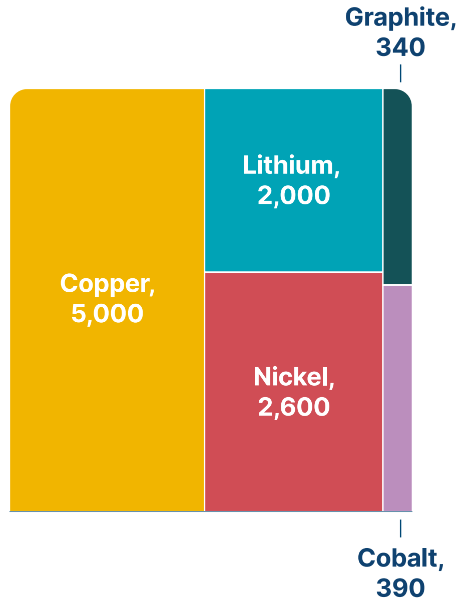
EXHIBIT 3.6

Up to $1.7trn of investment could be needed to expand mining, refining and recycling plants, 75% of which must be frontloaded this decade – unlocking a total market opportunity of $10trn

Investment requirements 2022–50¹
$ billion



Potential energy transition revenues 2022–50²
$ billion



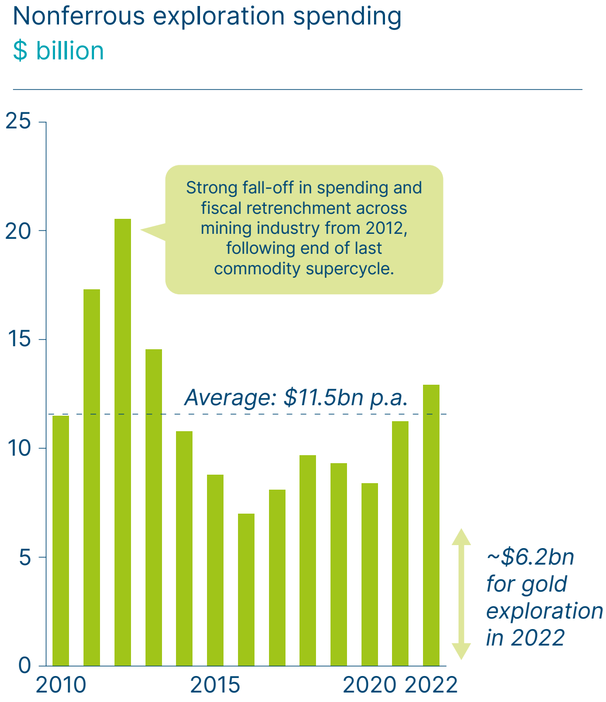
NOTES: ¹ Investment requirements are based on material demand only from the energy transition, and using historical average capital expenditures for mining, refining and recycling projects. ² Market size based on cumulative materials demand only from the energy transition (Copper = 600 Mt, Lithium = 20 Mt, Nickel = 100 Mt, Graphite 170 Mt, Cobalt = 6 Mt), and estimated average prices based on historical data (Copper = $8,500 per tonne, Lithium = $100,000 per tonne, Nickel = $26,000 per tonne, Graphite = $2,000 per tonne, Cobalt = $65,000 per tonne).

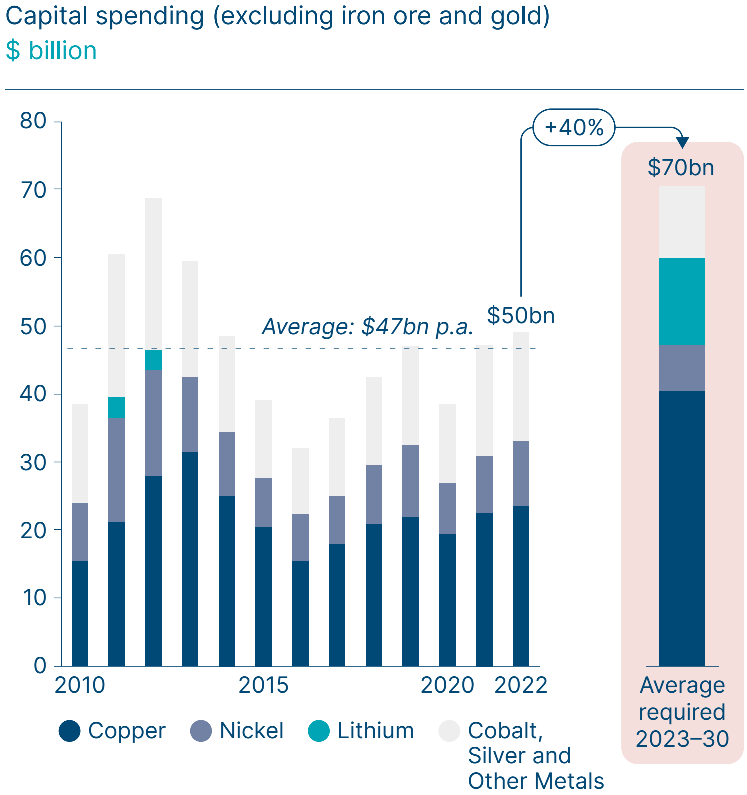
SOURCE: Systemiq analysis for the ETC, estimated based on average capital costs of existing projects and historical price averages.

116 Nonferrous refers to metals other than iron or steel.
117 S&P Global Market Intelligence (2022), *World exploration trends.*
118 ETC (2023), *Financing the transition.*
119 See also McKinsey & Co. (2022), *How to navigate mining's cash-flow conundrum.*

EXHIBIT 3.7

Spending by miners remains too low: annual mining capex needs to increase by $25bn per year through to 2030





SOURCE: Systemiq analysis for the ETC; Globaldata (2022); S&P Global Market Intelligence (2022), *World exploration trends*; S&P Global (2022), *Planned mining capital spending to fall $11B in 2023.*

Many markets for critical raw materials are small and illiquid, instead being driven by private deals between individual companies, as opposed to being traded on futures markets (e.g., the London Metals Exchange). This means companies and financial institutions do not have access to transparent information on market-wide demand, supply and prices to influence their decisions, contributing to insufficient investment.[120]

This is now being compounded as financial institutions look to ensure their investment portfolios are "Paris-aligned" and comply with various ESG considerations. Investing in the mining sector is often associated with reputation risks due to the potential for adverse environmental and social impacts (see Chapter 4), contributing to reduced investment.[121] For many financial institutions translation of these policies into practice simply excludes practices like mining, despite its necessity to the transition, in favour of less-risky assets (such as battery "gigafactories").

In addition, the sector is very early on in its transition to net-zero, creating disincentives for investment if financial institutions have targets to reduce their financed emissions. A challenge is the conflation of coal mining (which should be rapidly phased out this decade) and mining for critical raw materials (which is a critical enabler of the energy transition and must be rapidly scaled up this decade).[122]

Awareness and acknowledgement of the fundamental need for critical raw material mining to enable the energy transition is low across the financial and private sectors, and with the general public (as this report aims to address). This is reflected, for example, in the lack of efforts to define the role of mining in the EU's sustainable finance taxonomy.

Much greater efforts are required by policymakers and the private sector to change the narrative around mining for the energy transition. This can ensure that progress by financial institutions to implement transition plans does not have the counter-intuitive consequence of restricting investment in the materials which will enable it.

120 IRENA (2023), *Geopolitics of the energy transition: Critical materials.*
121 See e.g., Reuters (2020), *Miners face funding squeeze as green investing surges.*
122 See e.g., IIGCC (2023 – forthcoming), *Net zero standard for diversified mining.*

3.2.4 Declining mining productivity and cost and skill challenges

Three trends pose a challenge to raising existing mining output quickly and cost-effectively:

- The past two decades have seen a drop in **mining productivity** [Exhibit 3.8], as employment, capital and operating expenditures have all grown at a much faster pace than useful mining outputs, partly due to a combination of declining ore grades and very rapid expenditure growth during the early-2000s commodity boom.[123] Although this trend has reversed somewhat since 2010, overall productivity remains lower than in 2004.

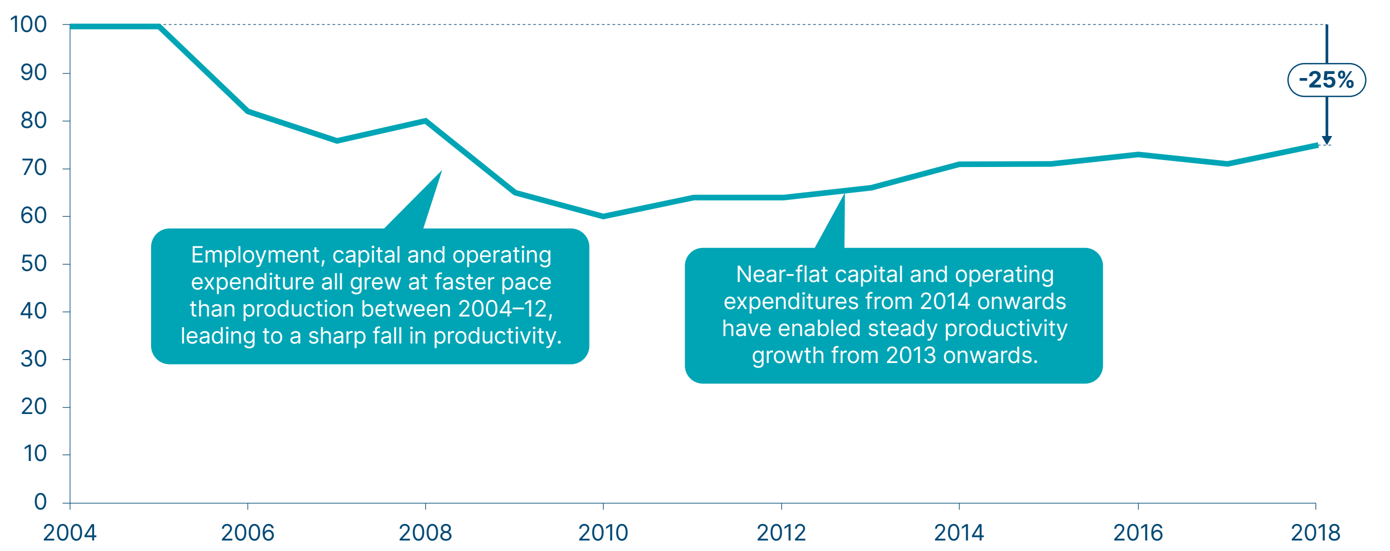
- Miners are struggling to attract sufficient high-quality talent, with a widespread **shortage of skilled engineers** across key mining countries, posing challenges when combined with high average ages for the existing workforce.[124]

- Over the shorter term, recent rises in interest rates are making financing more expensive, especially in some lower-income countries where mining is prevalent and the cost of capital is high. Higher input, shipping and freight costs throughout 2021–23 also pose **shorter-term challenges** to mining companies currently attempting to scale production.[125]

EXHIBIT 3.8

Mining productivity remains well below levels seen in early 2000s

Relative mining productivity[1]
2004 = 100



[1] As defined by McKinsey's MineLens Productivity Index, which accounts for physical mining output (total material moved), employment at mine sites, value of assets on site, and non-labour costs.

SOURCE: McKinsey & Co. (2020), *Has global mining productivity reversed course?*

123 McKinsey & Co. (2020), *Has global mining productivity reversed course?*; Calvo et al. (2016), *Decreasing ore grades in global metallic mining: A theoretical issue or a global reality?*
124 McKinsey & Co. (2023), *Has mining lost its luster?*; Wall Street Journal (2023), *A 'dirty' job that few want: mining companies struggle to hire for the energy transition.*
125 S&P Global (2022), *Mining companies pressured by inflation in 1st half of 2022.*

3.3 Actions to address supply side challenges

The challenges described in section 3.2 are, to a degree, inherent. But **public policy and industry action** can mitigate their severity by:

① Creating maximum possible clarity about future demand trends.

② Reducing mine development plans timescales.

③ Ensuring adequate finance for high priority developments.

④ Enhancing mining productivity via technical innovation.

⑤ Improved data sharing on an international basis can also help achieve all of these objectives.

3.3.1 Creating maximum possible clarity on future demand

Future demand for specific minerals is inherently uncertain, but public policy can at least reduce the range of uncertainty and provide strong indicators of likely areas of rapid growth by setting clear targets and mandates for key energy transition developments, including:

- **Targets** for the scale of wind and solar capacity to be in place by specific dates, supported by appropriate power market design and planning and permitting systems which can make those targets credible.
- Clear **strategies for the development of electricity transmission and distribution grids**, supported by regulatory regimes which allow investment ahead of demand.
- Strategies for the **development of green hydrogen**, which include both targets for electrolyser deployment and policies to support early demand offtake from high-potential sectors.
- Defined and **legislated dates** for banning the sale of light-duty transport ICE vehicles, (and subsequently heavy-goods ICE vehicles)[126] together with plans to ensure the rapid subsequent exit of existing ICEs from the vehicle fleet.

3.3.2 Reducing mine development timescales

Lengthy timescales involved in the development of many mines – in particular copper and nickel mines – reflect the multiple steps involved, many of which can be delayed by slow planning and permitting processes. In the case of nickel for instance, longer project timescales over the past decade have been caused predominantly by a doubling of the time required for feasibility assessments, from four to eight years.

Miners themselves can take many actions to reduce these timescales, through, for instance, optimising testing and commissioning processes to accelerate production ramp up.[127]

In addition, public policy in both high- and lower-income countries should focus on opportunities to streamline and accelerate project approval processes, while preserving high environmental standards. Key areas of focus should be:

- **Reducing timescales to obtain permits and achieve regulatory compliance** (e.g., environmental permits, mining licenses) through the digitalisation of processes, parallel rather than sequential processing where possible, and clear specification of maximum timescales for each process step. A key part of this will be ensuring local regulators/ government departments are adequately funded and staffed. The focus should be to ensure that a pro-active approach to sustainable and responsible mining, as outlined in Chapter 4, is rewarded with clear stage-gating and accelerated timescales from relevant government/regulatory bodies.

126 In the case of heavy-goods vehicles, there is a strong case for limiting the ICE ban to engines which burn any form of hydrocarbon fuel, but for allowing a potential future role for hydrogen ICEs.

127 Petavratzi and Gunn (2022), *Decarbonising the automotive sector: a primary raw material perspective on targets and timescales;* Heijlen et al. (2021), *Assessing the adequacy of the global land-based mine development pipeline in the light of future high-demand scenarios: The case of the battery-metals nickel (Ni) and cobalt (Co).*

- Facilitating early contact between miners and local electricity providers to **agree power purchase agreements** for low-carbon electricity.

- **Designating preferential development zones**, with accelerated approval timescales in areas with the least biodiversity and nature risks.

- **Encouraging development** in locations with a strong history of high-quality mining to allow accelerated construction, procurement of equipment and build-out of facilitating infrastructure (e.g. roads, railways, ports).

Together, such actions could significantly reduce the time required to bring new supply online. Roskill, a minerals and mining consultancy, estimate that fast-tracked nickel projects could be sped up by up to seven years, with the greatest potential acceleration across exploration, feasibility and financing stages.[128]

Such accelerated project timelines should not however come at the expense of essential social and environmental standards. Indeed, extensive community engagement and strong commitments to assess, minimise and monitor local environmental impacts should be a priority for all mining companies, and required by regulation. Chapter 4 considers the details of mining's local environmental impacts and how they can be reduced.

3.3.3 Ensuring increased public and private finance for high priority developments

The vast majority of finance for new mining developments can, and should, come from the private sector: around $70 billion of capital expenditure will be required each year between 2023–30 across copper, lithium, cobalt, nickel and graphite [Exhibit 3.7] – a $25 billion uplift from current annual spending. Indeed, many private sector companies are already taking actions which reduce mine development risks, and miners are beginning to invest greater amounts in energy transition metals.[129]

Beyond this, many automotive OEMs and battery manufacturers now have strategies to invest directly in raw material supplies, or are committing to long-term supply deals in "buyers clubs". However, as discussed in Chapter 3.2, while these can provide important future certainty for miners and refiners to encourage investment (and simultaneously reducing input cost volatility for manufacturers), they are unlikely to be a scalable solution to drive the significant increase in investment required across the whole sector globally.

The most critical action to underpin greater financing is for collaborative work from governments, financial institutions and the mining sector to proactively and clearly communicate the importance of sustainable and responsible metals mining for the wider energy transition.[130] They can do this by developing and promoting national critical raw materials strategies (e.g., as in the UK), making it a key agenda item in international forums (e.g., at G7/G20 meetings and UNFCCC COP discussions), and ensuring it has regulatory backing (e.g., in green taxonomies).

Actions from the financial sector include:

- **Ensuring financing activities reflect the necessary pathway to a net-zero economy**, recognising the critical need for much greater investment in mining for energy transition metals. As outlined in more detail in the ETC's *Financing the Transition* report, this should entail:[131]
  - Developing an understanding of what transition pathways for the mining and aluminium/steel sectors should look like and what this means for investment along this transition.
  - Focusing on a broad array of metrics (e.g., ratio of clean to fossil fuel investment), to prevent a sole focus on financed emissions targets, which could incentivise financial institutions to withdraw capital away from high-emitting mining sectors, as opposed to financing a sustainable scale-up during the transition.

- To address high cost of capital and lower risks, financial institutions and investors should **develop specific in-house expertise on sustainable and responsible mining**, including establishing on-the-ground teams in key mining countries, partnering with local governments, and developing clear criteria for sustainable responsible mining (see Chapter 4, Section 4.6).

128 Roskill/EU Joint Research Centre (2021), *Study on future demand and supply security of nickel for electric vehicle batteries.*
129 Spending by miners specialising in lithium, copper, nickel and cobalt rose from around $13bn to $18bn between 2021–22. IEA (2023), *World Energy Investment.*
130 See e.g., IIGCC (2023 – Forthcoming), *Net Zero Standard for Diversified Mining.*
131 ETC (2023), *Financing the Transition: How to Make the Money Flow for a Net-Zero Economy.*

- Financial institutions should be more proactive at **partnering with development finance institutions where greater de-risking is required**, for example financing junior minors in their exploration and development of new mines.
- The financial sector, in collaboration with the mining and downstream value chain, should explore the **development of new futures markets** across a wider range of critical minerals to help develop liquidity and deepen access to finance. The London Metals Exchange introduced a futures contract for lithium hydroxide in 2021,[132] and further such steps should be encouraged.

In addition, action from policymakers and public financial institutions is also required to accelerate progress and to address risks that the private sector is unable to absorb on their own.

- **Governments** can, and in some cases should, carry out direct **investments in specific mining or refining developments** which are almost certain to play a crucial role in the energy transition, particularly in those cases where there are concerns about security of supply [see Section 3.4].
  - **National infrastructure banks** can also support the development of domestic mining and refining capacity, even in high-income countries (e.g., funding exploration in the riskier stages of project development).
  - In certain cases, **government-led procurement** can also play a major role in providing certainty of large-scale demand for particular materials or projects – typically beyond the scale that private-sector buyers' clubs can reach.
- **Multilateral development banks and development finance institutions** should play a major role in de-risking mining projects in low-income countries, where investments can be held back by high cost of capital and political uncertainty. Multilateral Development Banks (MDBs) will need to play a critical role in financing the transition to net-zero across the developing world, and it is imperative that their strategies recognise and widely communicate that greater investment in mining for raw materials will play an important part of this.[133]

In particular, attention should be paid to de-risk projects where there is strong uncertainty: either around future demand trajectories, or where there could be a rapid scale-up in supply of recycled secondary materials, both of which could make project economics less favourable over the long-term.

3.3.4 Increasing mine output through increased efficiency and innovation

Given the long lead times for new mining projects, bridging supply gaps through to 2030 will require expanded production at many existing mines.

Achieving this to a large extent depends upon private company action to improve the details of mine operations, investing to increase feasible extraction rates, automating to improve operational efficiency and lower energy consumption and costs, and improving the anticipation and planning of maintenance related down time in order to increase utilisation rates.

Beyond this, the development of new technologies and processes can also play a major role. Three examples are:

- **Direct lithium extraction** (DLE) from geothermal brines: a method used to remove lithium from brines by bonding it to an extraction material, followed by use of a "polishing solution" to obtain lithium carbonate or hydroxide as an end-product. This approach could have faster production timescales and lower water consumption than current extraction methods (from salars or hard rock), but is still at an early stage with a variety of companies attempting to scale production.[134]
- Adopting **innovative and lower-carbon approaches for mining**, processing and refining – as being attempted by Lifezone Metals, who are developing a hydrometallurgy approach for a nickel project in Tanzania,[135] or by Ceibo, a company aiming to unlock deep-lying resources of copper sulphide deposits through new leaching methods.[136]
- Novel approaches to the **reprocessing of tailings and waste** can also play a major role. Freeport-McMoRan estimate they have up to 17 Mt of residual copper that could be extracted through new solvents and reagents or through re-processing (e.g., flotation), and globally this could reach around 57 Mt.[137]

In the case of deep-sea mining, the impacts of this form of extraction (including on carbon intensity and biodiversity) should be carefully considered, and weighed up against the equivalent trade-offs for land-based approaches to mining [Box G]. Any future deep-sea mining should proceed with strong caution and high standards for environmental impacts.

132 London Metal Exchange (2023), *EV metals*.
133 See Chapter 4 in ETC (2023), *Financing the Transition* for a detailed discussion of how MDBs can expand their financial capacity for the transition, de-risk investments and mobilise greater private investment.
134 McKinsey & Co. (2022), *Lithium mining: How new production technologies could fuel the global EV revolution;* Vera et al. (2023), *Environmental impacts of direct lithium extraction from brines*.
135 See e.g., Bloomberg (2022), *BHP-backed Lifezone takes over GoGreen in metals climate push*.
136 Ceibo (2023), *Leaching*.
137 The Economist (2023), *Copper is the missing ingredient of the energy transition;* Hann (2022), *Copper tailings reprocessing*.

Governments should be willing to support industry investments in these new technologies, increase investment in university-level research and encourage links between industry, universities and national laboratories. This action should build on strengths already present in countries such as Canada, Chile, Australia, Sweden and the USA, and extend them to other countries with mineral resources.

BOX G: Trade-offs for deep-sea mining should be carefully considered if exploration and production proceeds

This report focuses on the potential supply of land-based materials, along with associated challenges to their scale-up. With regards to the potential for deep-sea mining, the following points are key to understanding the trade-offs around the exploitation of deep sea resources:

- The resources of nickel, copper and cobalt available in the deep sea are larger than land-based resources,[138] and potentially lower-cost than certain existing sources of land-based production.[139]
- Although the supply scale-up challenge is significant over the short term, land-based resources are more than sufficient to meet cumulative future demand for critical raw materials from the energy transition[140] – exploiting deep sea resources in future would be a choice (with associated trade-offs), not an obligation.
- Some low level of exploitation of deep sea resources is likely to begin within the next few years, pending the finalisation of regulations for commercial deep-sea mining by the International Seabed Authority (ISA). However, initial production amounts are likely to be low and not able to significantly close supply gaps that might emerge by the late-2020s – large amounts of annual supply would likely come later.
- Plausible estimates suggest that in some cases the biodiversity and carbon life-cycle impacts of deep-sea mining[141] could be far lower than current land-based approaches to mining in the case of nickel, where around 50% of production is from Indonesia, where production is both carbon-intensive and leads to deforestation in high-biodiversity regions.[142]
- The key point to understand is that there are trade-offs associated with both existing approaches to land-based mining, and potential future deep-sea mining:
  - In the case of the former, Chapter 4 sets out the existing environmental and social impacts of mining, and how these could be reduced in order to achieve more sustainable and responsible mining.
  - For the latter, there is potential to introduce stringent regulation before starting any commercial deep-sea mining, setting a high bar for potential production and restricting it to well-understood, low-biodiversity areas of the deep sea.

The ISA's regulations should be developed as soon as possible in order to provide certainty and ensure high standards for sustainable and responsible deep-sea mining – and any future development of deep sea resources should proceed cautiously and with strong monitoring and oversight of impacts.

3.3.5 Improved international data sharing and collaboration

Better information, made more widely available, would improve the quality of investment decision making. Currently, many forecasts of demand and supply for energy transition materials are paywalled or proprietary – preventing both investors and policymakers from accessing trusted public sources of timely, high-quality information.

Key actions should include:

- **Publishing open demand and supply forecasts** and expanding access to data, spanning a range of plausible future pathways/scenarios and including regional analysis, should be a priority. This should follow the work done by the International Energy Agency and the International Renewable Energy Agency in the past few years with regards to the energy system and the role of renewable energy and fossil fuels within this,[143] and the Critical Mineral Tracker developed by Energy Monitor represents a good starting point.[144]

138 Royal Society (2020), *Future ocean resources;* British Geological Survey (2022), *Deep-sea mining evidence review.*

139 British Geological Survey (2022), *Deep-sea mining evidence review*; The Economist (2023), *Deep-sea mining may soon ease the world's battery-metal shortage.*

140 See Chapter 1, Exhibit 1.6, or British Geological Survey (2022), *Deep-sea mining evidence review.*

141 Specifically for mining of polymetallic nodules, a metal-dense cluster of rock, in the Clarion-Clipperton Zone – one of the regions designated for initial environmental impact assessments and feasibility studies for deep sea mining.

142 The Economist (2023), *The world needs more battery metals. Time to mine the seabed;* The Economist (2023), *Deep-sea mining may soon ease the world's battery-metal shortage;* Tempo (2023), *Illegal nickel laundering.*

143 See e.g. IEA (2021), *Net zero by 2050: A roadmap for the global energy sector;* IRENA (2022), *World energy transitions outlook.*

144 Energy Monitor (2023), *Energy Monitor's Critical Mineral Tracker.*

- **Convening ministerial meetings and industry-government conversations** could also help develop understanding and shape smart policymaking across different countries. For example, constructive discussions between consumer and producer countries, alongside key mining companies, could help develop new projects faster, whilst meeting higher environmental and social standards and guaranteeing future stability of demand or prices for companies.[145]
- **Government funding for new and updated geological surveys** – for example, in lower income countries where data is lacking, or in higher income countries that are looking to develop new mining capacity – and explore public-private partnerships to improve the use of satellite imaging, geophysical mapping and enable early-stage exploration to take place faster.

3.4 Geographic concentration and security of supply concerns

Economically viable raw material resources are often concentrated in specific countries. Raw material supply chains have therefore developed on a global basis with extensive international trade and major companies active in many locations. Sections 1 to 3 of this chapter have therefore focused on the challenge of balancing supply and demand at the global level.

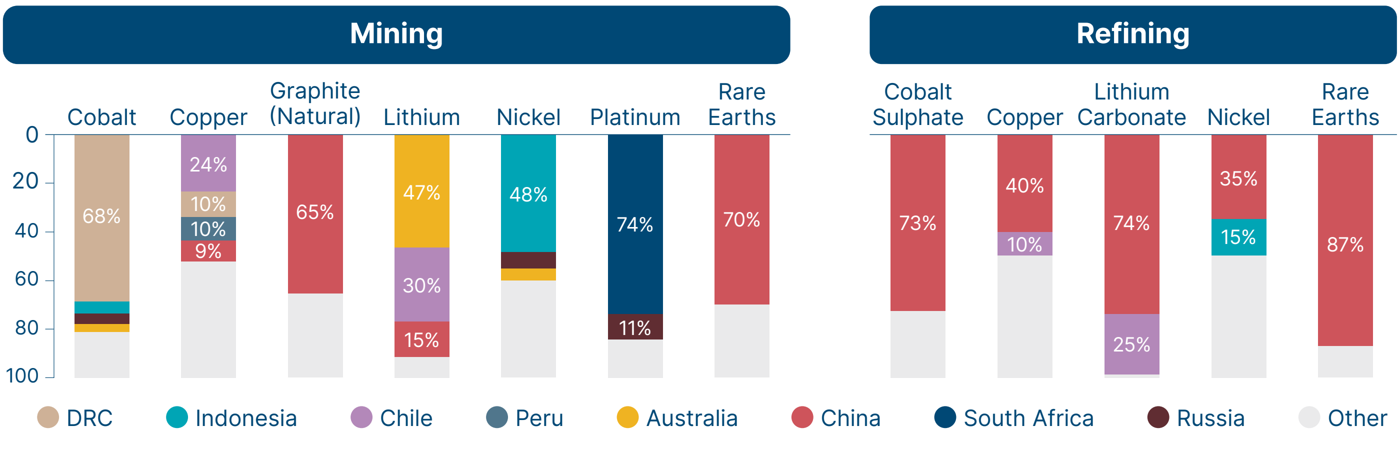
But there is heightened concern in many countries about the degree of geographic concentration which has emerged both [Exhibit 3.9]:

- At the **mining** stage, where a few countries dominate the production of specific commodities. For example, 70% of cobalt supply is from the DRC, and 70% of rare earths are mined in China.
- Even more so at the **refining and processing** stages, where China plays a dominant role across five key energy transition materials. This dominance reflects a combination of: China's lower capital, land and labour costs, which make it a low cost producer of many processed and manufactured goods; China's long-standing government support for clean energy industries, which have driven a dramatic rise of domestic solar PV and battery production; and looser environmental standards imposed (at least in the past) on some refining processes.[146]

EXHIBIT 3.9

Mining and refining of key raw materials is highly concentrated, exposing global markets to supply disruption risks

Share of global mining and refining production by country, 2022
%



SOURCE: US Geological Survey (2023), *Mineral Commodity Summaries*; IEA (2021), *The role of critical minerals in clean energy transitions*; BNEF (2022), *Localising clean energy supply chains comes at a cost.*

Such high levels of concentration increase the risk of supply shortages relative to demand. Geopolitical tension could generate policy responses which restrict the supply and increase the price of specific commodities. Political instability and resource nationalism can disrupt supply. And localised issues, ranging from drought to unstable power supply, can knock out supply from a particular region or country.[147]

145 Financial Times (2023), *No country can solve critical mineral shortages alone.*
146 ETC (2023), *Better, faster, cleaner: Securing clean energy supply chains.*
147 IRENA (2023), *Geopolitics of the energy transition: Critical materials.*

Four examples of such disruptions from recent years are:

- **Russia's invasion of Ukraine**, which produced a large spike in nickel prices since Russia is the world's third-largest producer, with around 10% of global production.[148]

- **Drought across northern Chile** through 2021–22 which contributed to lower than expected output from many mines, restricting global copper supply.[149]

- A ten-fold increase in prices of **neodymium** and other rare earth elements in 2010 following a large **reduction in export quotas** by the Chinese government.[150]

- **Protectionist measures** by a variety of governments, most recently including the Indonesian government banning export of nickel ores,[151] the US Inflation Reduction Act local content requirements for battery supply chains [Box H], the Government of Bolivia forcing the inclusion of the state lithium company in resource development,[152] or the Government of Zimbabwe banning export of unprocessed lithium.[153]

To date, such disruptions have tended to produce impacts on the market for specific minerals, sometimes only on a national/regional level, and for only a short time. But as demand for key energy transition materials rises rapidly in the coming decade, there is a real risk that highly concentrated supply, combined with rising trade tensions, could lead to major supply shortages affecting several commodities at the same time, disrupting and delaying the energy transition.[154]

3.5 Actions to build resilient and secure supply chains

In recent years, several factors have increased government and company focus on the dangers created by the geographical concentration of supply. These include:

- **The COVID-19 pandemic** and associated supply chain disruptions, which highlighted the fragility of supply chains across a wide range of goods.[155]

- Heightened **geopolitical tensions** between the USA and China.[156]

- **Russia's invasion of Ukraine** and the resulting high energy prices in Europe and elsewhere, which have led to a desire to develop more secure energy supplies.[157]

In response, many governments are now introducing policies which attempt to create more "resilient" and "secure" supply chains, including via protectionist measures, for many categories of products and technologies, including semiconductors and energy related final products (e.g., solar PV panels and electric vehicles) as well as materials:

- The **Inflation Reduction Act** was passed in the USA in August 2022, including tax credits for low-carbon electricity generation and domestic mining and manufacturing [see Box H]. This is part of a wider suite of policies, including the Infrastructure, Investment and Jobs Act and the CHIPS & Science Act, which are aimed at securing supply chains and increasing industrial competitiveness.[158]

- The EU Commission's Green Deal Industrial Plan, which includes both the **Critical Raw Materials Act** and the **Net-Zero Industry Act** – both of which contain requirements for increasing domestic production and manufacturing.[159] These targets do not aim for full domestic self-sufficiency, and if achieved would be a good step forward in terms of diversification and reduction in risk from concentrated supply.

148 This was also caused in part by trading abnormalities on the London Metals Exchange. IEA (2022), *Share of global production and rank for selected minerals and metals in Russia;* Bloomberg (2022), *The 18 minutes of trading chaos that broke the nickel market*; S&P Global (2022), *Nickel price spike during Russia-Ukraine conflict could drive up EV costs.*
149 See e.g., Mining.com (2023), *Giant Chile mines are struggling just as world needs more copper;* Antofagasta (2023), *Quarterly production report – Q4 2022.*
150 Shen et al. (2020), *China's public policies toward rare earths, 1975-2018.*
151 National Bureau of Asian Research (2022), *Indonesia's nickel export ban.*
152 The Economist (2021), *How Bolivian lithium could help fight climate change.*
153 Africa News (2023), *Zimbabwe bans all lithium exports.*
154 For example, a study of different kinds of disruptions to rare earth element supply could lead to increased prices and reduced production of high-strength magnets for several years, potentially influencing wind turbine and EV deployment. Riddle et al. (2021), *Agent-based modelling of supply disruptions in the global rare earths market.*
155 ETC (2023), *Better, Faster, Cleaner: Securing clean energy technology supply chains;* JP Morgan (2022), *What's behind the global supply chain crisis.*
156 Bipartisan Policy Center (2022), *Inflation reduction act summary: Energy and climate provisions.*
157 ETC (2022), *Building energy security through accelerated energy transition.*
158 Kaya Advisory/Inevitable Policy Response (2022), *The US discovers its climate policy: A holistic assessment and implications.*
159 The Critical Raw Materials Act requires domestic production to meet 10% of total supply for mining, 40% of total supply for refining, and for recycling to meet 15% of metals supply in 2030. The Net-Zero Industry Act requires domestic manufacturing to meet 40% of requirements in 2030. See also ETC (2023), *Better, Faster, Cleaner: Securing clean energy technology supply chains – EU Policy Toolkit.*

- **The Government of India has introduced a Production Linked Incentive** scheme to boost domestic manufacturing, including for electric vehicles and solar PV modules (where it has also introduced tariffs on modules imported from China).[160]

- The government of **South Korea** has introduced a critical minerals strategy with the aim of reducing import dependence from key countries, especially China, down to 50% by 2030 (from 80% currently), and increase the share of recycled supply up to 20% by the same date (from 2%).[161] Such steps are positive in terms of diversification and risk management of supply.

BOX H: The US Inflation Reduction Act

The passage of the US Inflation Reduction Act (IRA) in 2022, as part of a wider suite of energy transition and infrastructure spending, has been one of the most significant announcements of recent years to accelerate climate and energy policy.

Together with wider federal and state programs, this amounts to a trillion-dollar public investment in the energy transition [Exhibit 3.10, LHS]. Specifically relating to critical raw materials for the energy transition, the act provides a subsidy to cover 10% of production costs for a range of critical raw materials, and also provides up to $7,500 in consumer subsidies for the purchase of electric vehicles, provided the supply chains for critical minerals, batteries and vehicles meet certain local content or free trade partner agreements [Exhibit 3.10, RHS].[162]

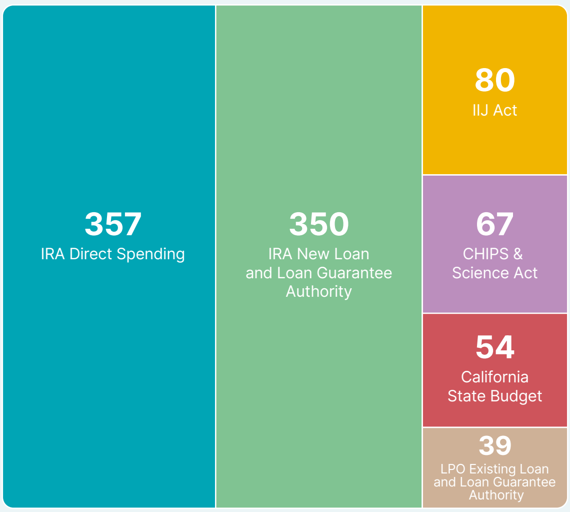
The US has recently been involved in discussion with the European Union in order to clarify whether certain IRA subsidies would be available to European companies or to supply from Europe, under the specification that these are available to countries with free-trade agreements with the US.[163]

EXHIBIT 3.10

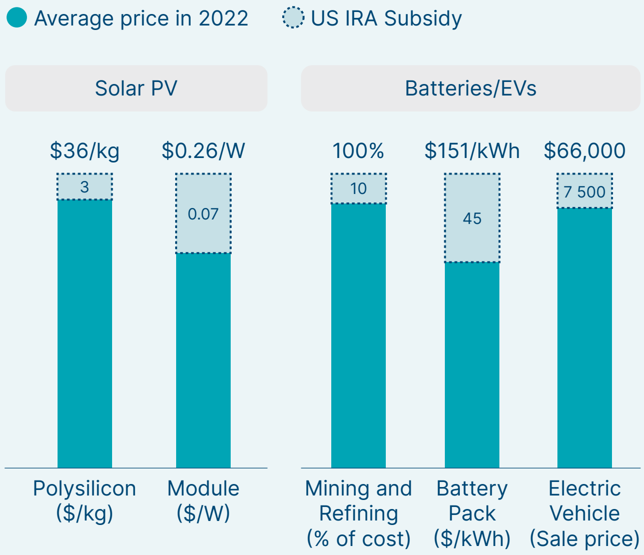
The US Inflation Reduction Act offers generous subsidies for domestic mining, refining and manufacturing projects

State and federal climate and energy spending capacity
$ billion

Total of ~$1 trillion in spending capacity available



US Inflation Reduction Act subsidies for solar PV and batteries
Average price in 2022 and US IRA subsidy available



NOTE: IRA = Inflation Reduction Act; IIJ = Infrastructure, Investment and Jobs; CHIPS = Creating Helpful Incentives to Produce Semiconductors; LPO = Loan Programs Office.

SOURCE: Kaya Advisory/Inevitable Policy Response (2022), *The US discovers its climate policy: A holistic assessment and implications*; BNEF (2023), *Solar prices finally fall*; BNEF (2022), *Lithium-ion battery price survey*; BNEF (2022), *Localizing clean energy supply chains comes at a cost.*

160 Ministry of Heavy Industries, Government of India (2022); PV Magazine (2022), *Indian government approves second phase of solar manufacturing incentive scheme.*
161 Ministry of Trade, Industry and Energy (2023), *Korea announces measures for securing critical minerals supply.*
162 The full credit is split in two halves: EV manufacturers must meet a threshold for sourcing critical minerals from North America and free-trade agreement countries for half of the credit (requirement rises from 40% in 2024 to 80% in 2026), and must meet a threshold for sourcing battery components only in North America for the other half (requirement rises from 50% in 2024 to 100% in 2028).
163 See e.g., American Enterprise Institute (2023), *The US-EU Inflation Reduction Act patch-up.*

These policies seek to build supply capacity either domestically or in countries deemed to be close geopolitical allies ("nearshoring" or "friend-shoring"). In many cases, these policies are focused on employment creation and the rebuilding of competitive manufacturing capacity, as well as on making supply chains more "secure".

In some cases, these policies are bound initially to increase the cost of some inputs to the energy transition, since they limit the ability to source products, components or materials from the lowest-cost location – and could lead to trade tensions across key regions.[164] However, in the long-term they could increase the pace of the energy transition by increasing the total amount of investment devoted to innovation in key technologies.

The objective in detailed policy design should therefore be to maximise the benefits while minimising adverse short-term cost effects. The ETC's recent report on clean energy technology supply chains sets out guidelines for how to achieve this.[165]

In relation to raw material supplies, the priorities should be to:

- Develop company and country strategies to **secure and diversify** mineral supplies.
- Where deemed strategically beneficial, develop domestic capacity and **nearshoring strategies** which achieve maximum benefits while reducing or minimising costs.

3.5.1 Strategies to secure and diversify supply chains

Different countries are more or less endowed with particular materials, making some geographical concentration of supply inevitable. However, companies and countries can act to secure future mineral supplies, and should view diversification first and foremost through the lens of risk management:

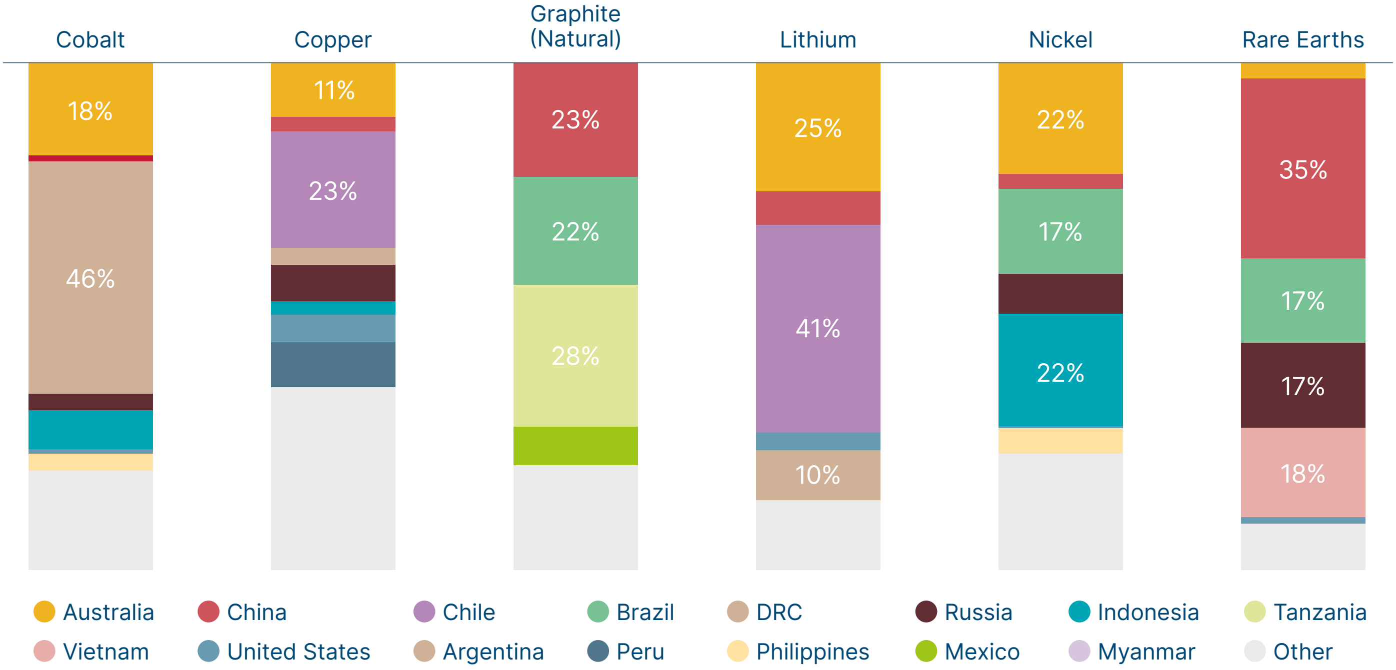
- Global **reserves** for many minerals are much more widely distributed than current mine production [Exhibit 3.11] – indicating potential for diversification. However, two challenges must be overcome:
  - Geographic distribution of production is typically governed by economics; least-cost locations will always be favoured, making diversification potentially reliant on additional government support, as outlined above.
  - Long timescales involved in exploration and development of new mine sites limit the feasible pace of diversification. For some materials in particular (e.g., copper and nickel), action can have only a limited impact on the distribution of mine production before 2030.
- The potential to diversify **refining** is higher. Timescales to build a refinery are shorter, so increased capacity could easily be built either at mine sites in producing countries (e.g., to increase overall value of end products for miners), or in countries where demand for refined materials is high (e.g., close to battery and electric vehicle manufacturing plants).
- The focus thus far, however, has been on downstream manufacturing, especially of batteries. For example, one study estimates that based on current plans both the EU and US could meet domestic deployment targets for electric vehicles and batteries - but would still be reliant on imports for both mined and especially refined materials.[166] This highlights the importance of investing in **diversifying the entire value chain**: mining and refining as well as gigafactories.

164 IMF (2023), *Green trade tensions.*
165 ETC (2023), *Better, Faster, Cleaner: Securing clean energy technology supply chains.*
166 Chatham House/ResourceTrade.Earth (2023), *Cobalt refining power gives China an advantage in the race for EV battery dominance.*

EXHIBIT 3.11

There is an opportunity to diversify future mining, with a wide global distribution of mineral reserves

Global distribution of mineral reserves
%



SOURCE: US Geological Survey (2023), *Mineral Commodity Summaries*.

It is clearly feasible for companies to seek to secure and diversify their sources of mineral supply. This will entail using the supplier management techniques including direct vertical integration and long-term fixed price contracts, but with a deliberate focus on achieving a more geographically diverse supply. Three strategies include:

- **Joint ventures:** Two or more mining companies join forces to exploit a particular resource, potentially combining complementary backgrounds, expertise or financing capabilities. For example, Tianqi Lithium Corporation and IGO Ltd. have formed a joint venture to develop and operate new lithium assets.[167]

- **Direct investments and vertical integration:** Several manufacturers have made investments in specific mines or mining companies, in order to control future supply more directly. For example, the auto manufacturer General Motors is planning to spend $650 million for a stake in Lithium Americas, a company that is developing a large lithium mining project in Nevada.[168]

- **Off-taker agreements:** Manufacturers sign direct agreements with individual companies in order to secure large volumes of supply at a fixed price over a given period. For example, Tesla has signed off-taker agreements for cobalt with Glencore, and for nickel with Vale, two of the world's largest mining companies.[169] In certain cases, these can be tied to particular requirements around sustainable and responsible supply of materials, for example, by requiring particular third-party audits and certifications.

- In certain cases, governments or companies could consider forms of **price insurance**, providing guarantees or minimum levels of price to secure supply – providing stability and certainty to producer companies or countries, unlocking supply that otherwise may not be available.

Governments can also encourage and support these objectives – critical minerals supply has taken gathered increased political attention recently. Initiatives include:

- The **UK and Canadian** governments signed an agreement to increase cooperation, accelerate research and innovation, increase information sharing and create stronger links across industries and companies.[170]

167 See igo.com.au (2020), *Lithium joint venture with Tianqi Lithium Corporation.*
168 Techcrunch (2023), *GM invests $650M in lithium mining to lock down EV raw materials.*
169 Mining.com (2022), *Tesla inks secret multi-year nickel supply deal with Vale;* Financial Times (2020), *Tesla to buy cobalt from Glencore for new car plants.*
170 UK Department for Business and Trade (2023), *UK and Canada sign agreement to boost green tech supply chains.*

- From a more geo-strategic trade perspective, the US Department of State is developing a **Minerals Security Partnership** that aims to increase mining, processing and recycling capabilities in strategically-aligned countries – mainly by catalysing investment throughout minerals supply chains from governments and the private sector.[171]

- The EU Critical Raw Materials Act includes provisions for a "Critical Raw Materials Club" to bring together countries to scale production of key energy transition metals, including potentially up to €20 billion of investments by 2030.[172]

- The recent G7 summit in Japan included a five-point plan for critical minerals security, covering supply-demand forecasts, sustainable supply chains, increasing innovation and recycling, and preparing for supply disruptions – as well as a pledge of $13 billion of investments in critical minerals supply by G7 governments.[173]

With such a range of initiatives, and with upcoming G7/G20 meetings providing further opportunities for discussion, there could be further scope to align government initiatives and scale sustainable critical minerals supply.

3.5.2 Maximising the benefits of nearshoring

Nearshoring involves the expansion of domestic production across supply chains, including upstream mining and refining for critical minerals. Whereas diversification of supply is highly likely to be beneficial whenever possible, nearshoring may in some cases involve a trade-off between increased costs and the benefits of increased supply security and employment creation.[174]

Thus, where nearshoring is deemed strategically beneficial, governments and countries must carry out rigorous assessments of what is feasible and how to manage the trade-offs involved. This will require:

- A strong focus on **maximising recycling**, increasing the future use of secondary materials and reducing future dependence on imported primary materials. The changes needed to achieve this were discussed in Chapter 2.5.

- Government support for **detailed assessment of mineral resources** within the country and of their technical and economic feasibility of extraction. Many developed countries do have significant reserves of currently underexploited minerals – in particular lithium – but in some cases comprehensive information on resource availability is still lacking.

- Government and industry finance of **research into new extraction technologies** which can widen the range of resources available, and reduce local environmental impacts (see also Section 3.3.4 – many of these innovations are judged to have lower life cycle impacts for resource extraction).

- Setting **targets for local sourcing, but introduced gradually** and on the basis of realistic assessments of supply availability, avoiding the risk that unrealistic obligations will create supply shortages and rapid price increases on a local level.

- Realistic assessment of the potential to **build refining capacity** as much as mining capacity, given this can be done on much shorter timescales than new mining capacity.

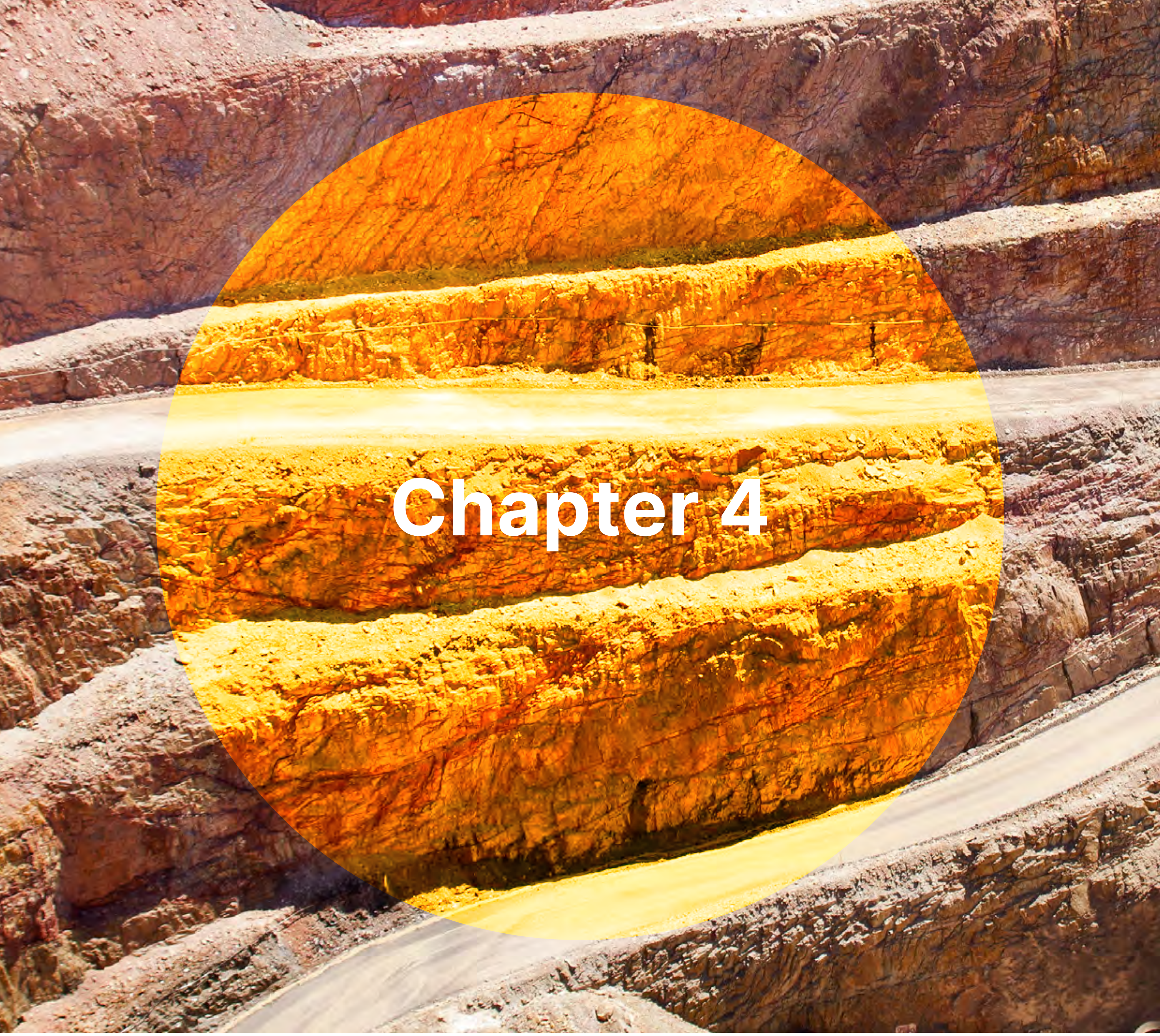
- **Accelerated planning and permitting** policies, combined with tight and well enforced environmental standards, which can make possible rapid development of both mining and refining projects in areas with promising resources.

    - For example, the Salton Sea in the USA has an estimated 2 Mt of total lithium resource (enough for over 300 million electric vehicles),[175] or the yet-to-start Rönnbäcken nickel-cobalt project in Sweden, which could supply 23 kt of nickel each year (enough for 640,000 electric vehicles).[176]

- In extreme cases, governments seeking to ensure security of supply can also consider holding **stockpiles** of the most critical raw materials, although this is a far-from-optimal solution that tends to introduce artificial scarcity into markets.

Even with policies of this type in place, there will still be major international trade in raw materials and significant concentration of supply for some of them. But well-designed policies could over a number of years significantly reduce today's very high levels of concentration.

171 US Department of State (2022), *Minerals Security Partnership.*
172 EE News (2023), *EU to form €20bn critical materials club.*
173 Japan Ministry of Economy, Trade and Industry (2023), *Annex to the Climate, Energy and Environment Ministers' Communiqué – Five-point plan for critical minerals security;* S&P Global (2023), *INTERVIEW: Japan to boost critical minerals security with G7, 'like-minded countries'.*
174 The trade-offs involved in nearshoring are discussed further in ETC (2023), *Better, Faster, Cleaner: Securing clean energy technology supply chains.*
175 Assuming 60 kWh batteries and a lithium intensity of 0.1 kg/kWh. McKibben et al. (2020), *Lithium and other geothermal mineral and energy resources beneath the Salton Sea.*
176 Assuming 60 kWh batteries and a nickel intensity of 0.6 kg/kWh. Bluelake Mineral (2022), *Bluelake Mineral announces positive PEA for the Rönnbäcken nickel-cobalt project.*



Minimising and managing environmental impacts of materials supply

The transition to a low-carbon, highly electrified energy system will mean a shift away from consumable fossil fuels, which have to be mined continuously to operate the energy system every single year, to a system based on durable metals, which can and should be re-used and recycled at end of life. By reducing the amount of primary materials we need, and by improving the way in which we supply mined materials, environmental impacts can be reduced over coming decades.

As Chapter 1 outlined, the long term environmental impact of raw material extraction to support the energy transition will be far less than that imposed by the fossil fuel-based system. In essence the transition to a net-zero, highly electrified energy system will mean a shift away from consumable fossil fuels, which have to be mined continuously to operate the energy system every single year, to a system based on durable metals, which can and should be re-used and recycled at end of life.

But growing demand for energy transition materials will have significant local environmental and social impacts. The scale of such impacts will depend on a range of factors:

- The **type of mineral ore**, which dictates the chemistry of the rock and the refining and processing required to extract valuable commodities from it.
- The **ore grade**, which defines the proportion of commercially valuable material within a volume of rock.
  - For example, copper ores tend to contain roughly 0.6% elemental copper, whereas bauxite contains around 50% alumina (or, 25% elemental aluminium) – leading to very different volumes of ore and material that need to be moved and processed for every ton of metal.[177]
  - As ore grades decrease, the energy, emissions and water intensity required to obtain one ton of metal will increase.[178]
- **Local geography**, for example, proximity to inhabited areas, areas of high biodiversity, or locations in water-scarce regions. Proximity of mining to indigenous people can have significant social implications.
- **Site operations** – for example, if the mining approach is open-pit or underground, the carbon intensity of the source of power used to run operations, and factors relating to worker health and safety, working conditions and human rights.
- Political factors and the **strength of institutions and governance** in mining countries, which can determine the strength of environmental and social regulations (e.g., human rights laws or enforcement of environmental standards).

In total, the local environmental impacts could be large and in some cases significantly adverse if not well managed. Further, these impacts can pose a risk to the required scale-up in mining for the energy transition for several reasons:

- **Downstream demand pressures:** OEMs, consumers and investors can refuse to accept supplies of high-impact materials, if impacts are not managed or mitigated as far as possible.
- **Regulation** can also exclude materials with high environmental or social impacts. For example, the US Dodd-Frank Act passed in 2010 contains a provision on supply chain risks for certain conflict minerals (tungsten, tantalum, tin and gold), and the upcoming European Battery Regulation will require carbon footprint and supply chain due diligence monitoring for electric vehicle batteries.
- **Local communities** can also delay, or even stop, prospective mining projects due to local environmental concerns, as has happened recently for the Thacker Pass lithium mine in Nevada,[179] and the Jadar lithium project in Serbia.[180]

The key to meeting material requirements for the energy transition at the pace required is, therefore, to expand supply as sustainably as possible in order to unlock new, high-quality projects quickly and responsibly, with the buy-in of both local mining communities and wider society.

It is therefore essential to reduce the required extraction by maximising technical efficiency and recycling in the way described in Chapter 2, and then by minimising environmental and social impacts per ton of each material extracted.

This chapter identifies the different categories of potential environmental impacts, and the actions which companies and governments can take to reduce them.

177 Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes.*
178 Calvo et al. (2016), *Decreasing ore grades in global metallic mining: a theoretical issue or a global reality?;* IEA (2023), *Energy technology perspectives.*
179 Inside Climate News (2021), *Plans to dig the biggest lithium mine in the US face mounting opposition.*
180 Financial Times (2022), *Rio Tinto warns of delay to Serbia lithium project.*

It covers in turn:

1. The impact of materials supply on greenhouse gas emissions
2. Impacts of mining on land use and biodiversity
3. Local pollution effects – toxic effluents and air quality
4. Water consumption for mining
5. Impacts on local communities and society
6. Five priority areas for sustainable and responsible materials for the energy transition
7. Actions companies, governments, and the wider materials supply chain must take to measure, manage and reduce impacts

4.1 Greenhouse gas emissions from materials production

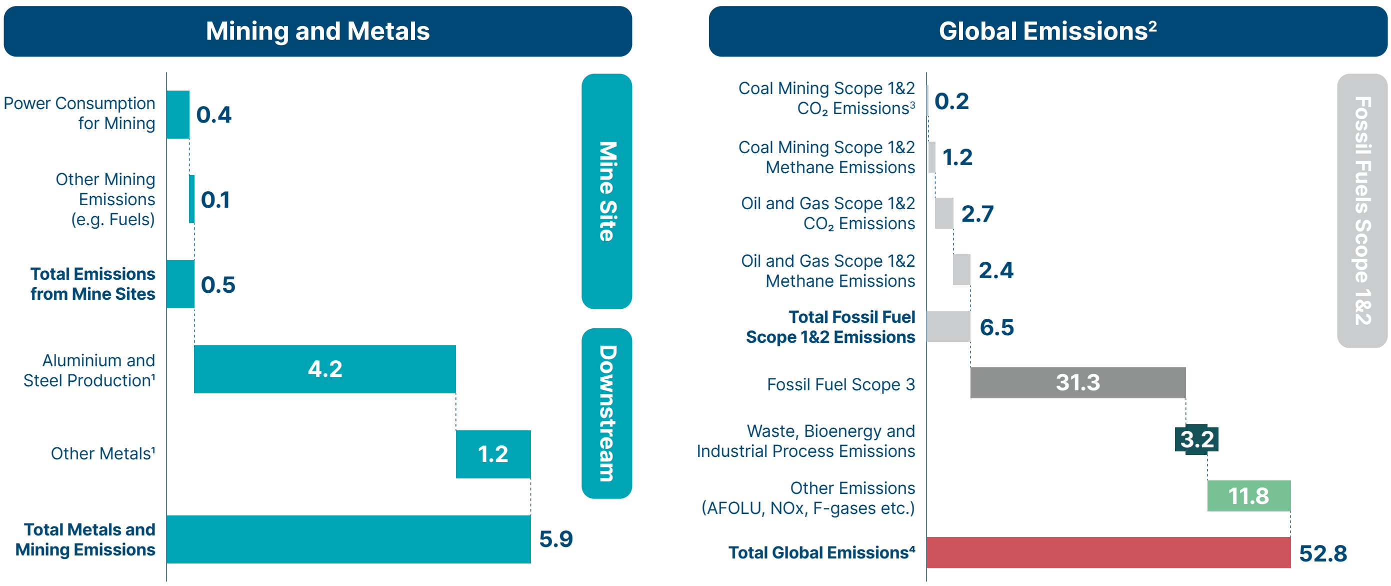
Total emissions from mining operations today, including for non-clean energy purposes, contribute about 0.5 Gt of CO_2e per annum, while the downstream production of steel and aluminium and other end-use materials contributes an additional 5.4 $GtCO_2$ [Exhibit 4.1]. This compares with about 6.8 $GtCO_2e$ of scope one and two emissions resulting from fossil fuel production, and another 34 $GtCO_2e$ per annum resulting from fossil fuel combustion and industrial applications.

Expanding use of materials to support the energy transition will result in significant one-off additional emissions. Exhibit 4.2 sets out our estimate of these emissions for production of materials, noting the potential to reduce cumulative emissions by more than half by decarbonising supply chains and reducing materials use. For completeness, these estimates are based on emissions from both mining and processing/refining – the latter process often being very energy- and emissions-intensive for certain materials, notably battery materials and polysilicon.[181]

EXHIBIT 4.1

Emissions from metals mining and production are ~10% of global GHG emissions and dominated by downstream production

Annual GHG emissions from metals and mining compared to fossil fuel production
$GtCO_2e$



NOTE: AFOLU = Agriculture, Forestry and Other Land-Use. [1] Including electricity consumption; [2] Using a GWP100 value of 30 for methane; [3] Coal production and transport CO_2 emissions are estimated as ~1.4% of life-cycle emissions, based on US Congressional Research Service (2015), *Life-cycle GHG assessment of coal and natural gas in the power sector* and using total coal emissions of 15.5 $GtCO_2$ from IEA (2023), *CO_2 Emissions in 2022*; Coal mining methane emissions are taken separately from McKinsey & Co. (2020), *Climate risk and decarbonisation: What every mining CEO needs to know*; [4] Total global GHG emissions of 52.8 $GtCO_2e$ are from 2021. Total energy-related GHG emissions in 2022 were 41.3 $GtCO_2e$.

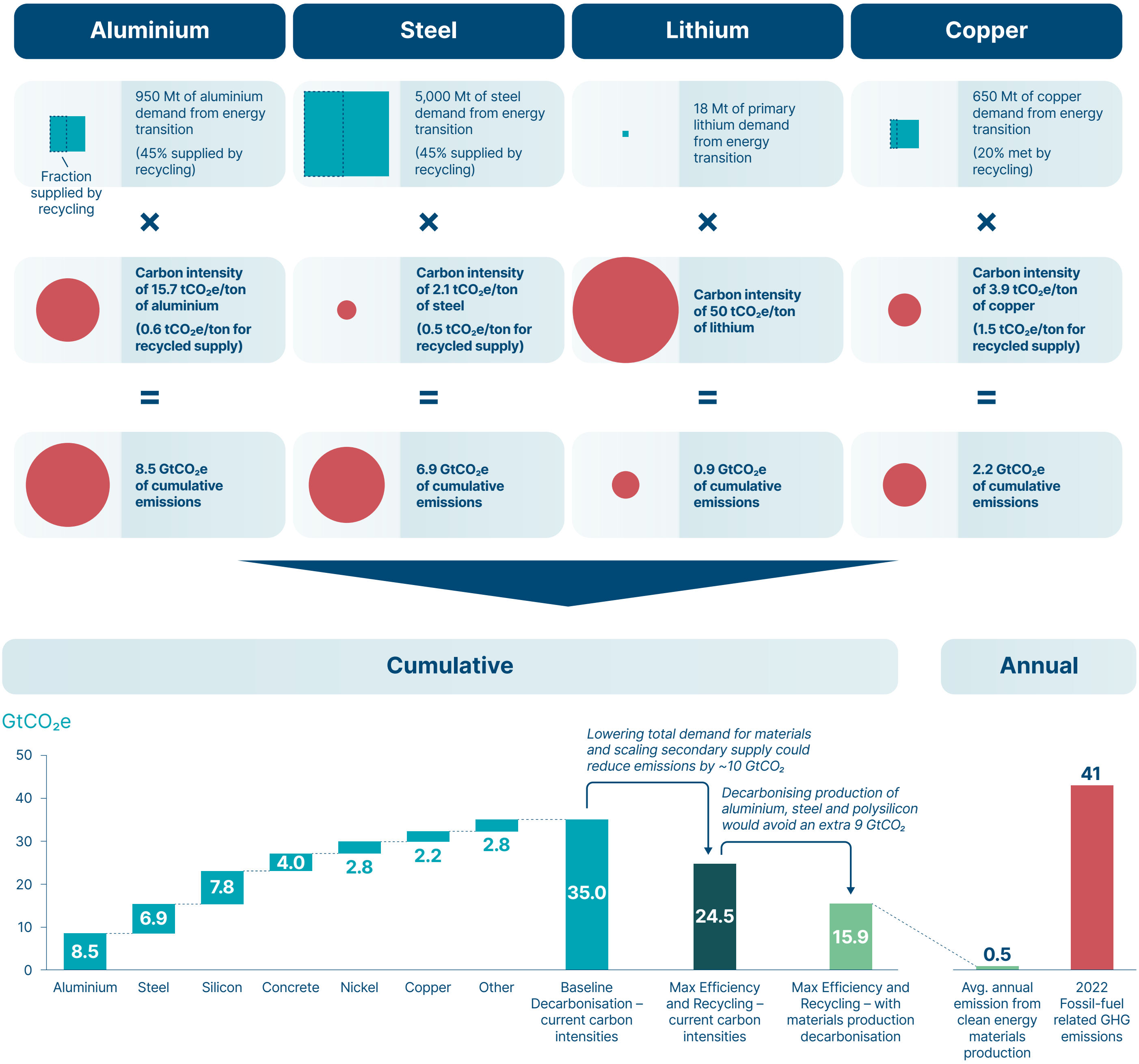
SOURCE: Systemiq analysis for the ETC; MPP (2022), *Pathways to Net Zero (Aluminium, Steel)*; Azadi et al. (2020), *Transparency on GHG emissions from mining to enable climate change mitigation*; IEA (2023), *Scope 1 and 2 GHG emissions from oil and gas operations in the Net Zero Scenario, 2021 and 2030*; IEA (2023), *Global Methane Tracker*; IEA (2023), *CO_2 Emissions in 2022*; UNEP (2022), *Emissions gap report 2022*; McKinsey & Co. (2020), *Climate risk and decarbonization: What every mining CEO needs to know.*

181 For example, the production of nickel from laterites, typically done via high pressure acid leaching or via nickel pig iron, is very electricity-intensive and can emit 15–60 tCO_2e per tonne nickel, in part due to heavy use of coal power in Indonesia, the dominant global producer of nickel. IEA (2021), *The role of critical minerals in clean energy transitions*; Minviro (2021), *Shifting the lens;* Porizio and Scown (2021), *Life-cycle assessment considerations for batteries and battery materials.*

EXHIBIT 4.2

Innovation, recycling and decarbonisation would lead to cumulative emissions from producing clean energy materials that are half of annual fossil fuel emissions

Emissions for production of energy transition materials 2022–50[1]



[1] Emissions intensity is based on life-cycle emissions for production of end-use material, i.e. includes both mining and processing/refining. For aluminium, steel and copper, carbon intensities for both primary and secondary supply are used in combination with assumptions about the volume of cumulative demand 2022–50 that will be met by secondary supply.

NOTE: The ETC's Baseline Decarbonisation scenario assumes an aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. The Maximum Efficiency and Recycling scenario assumes accelerated progress in material and technology efficiency, and recycling clean energy technologies/materials.

SOURCE: Systemiq analysis for the ETC; MPP (2022), *Making Net-Zero Steel/Aluminium Possible*; IFC (2023), *Net zero roadmap to 2050 for copper and nickel mining value chains*; IEA (2021), *The role of critical minerals in clean energy transitions*; Minviro/Livent (2022), *Growing responsibly – 2021 Sustainability Report*; IEA (2023), *CO_2 emissions in 2022.*

As an upper bound, if the current emissions intensity of materials production remained the same to 2050, the total cumulative additional emissions amount to at most 35 $GtCO_2e$ between now and 2050 [Exhibit 4.2]:

- A major part of this derives from the additional production of **aluminium** (8.5 $GtCO_2e$), **steel** (6.9 $GtCO_2e$) and **concrete**[182] (4 $GtCO_2e$) which will be needed to build a low-carbon energy system. For all three materials, these are a small subset of total emissions from these sectors which are dominated by non-energy related applications.

- **Polysilicon** production, a major input to solar panels, currently dominated by coal-powered supply chains in China, would also generate significant cumulative emissions of around 8 $GtCO_2e$.

- **Copper and nickel** production is the next most significant factor, each with around 2 and 3 $GtCO_2e$ of cumulative emissions, respectively, while all the other materials together produce around 3 $GtCO_2$ – even accounting for carbon-intensive materials such as lithium or neodymium.

The relatively small emissions of many of the materials reflects the small total volumes consumed, which offsets often high emissions per tonne produced – as illustrated in Exhibit 4.2 in the case of lithium.

These additional emissions will to a significant extent be "one-off" in nature as the clean energy system is built, and would decline over time as the world's energy system reduces its emissions intensity – and as the share of recycling increases.[183] Thus, once the large-scale expansion of a clean power system has been achieved, the material extracted to build clean energy technologies will remain in use for many decades and can be recycled at end-of-life; and while the first generation of batteries is in some cases being manufactured using electricity with high carbon intensity, as electricity systems continue to decarbonise, the manufacture of batteries, electrolysers, solar panels and other products will become a near-zero carbon activity.

However, 35 $GtCO_2e$ of additional cumulative emissions is still significant in a world where IPCC estimates suggest that we only have about 400 $GtCO_2$ of cumulative carbon budget left if we are to have a 50:50 chance of limiting global warming to 1.5°C.[184]

It is therefore essential to minimise this cumulative emissions impact via:

- Improvements in technical efficiency and recycling which reduces the demand for primary materials as much as possible. These actions were considered in Chapter 2, and could reduce total cumulative emissions by 30% from 35 $GtCO_2e$ to around 25 $GtCO_2e$ (at current emissions intensities).

- Actions to reduce the carbon intensity of production, and in particular of the big contributors to cumulative emissions – steel, aluminium, concrete and polysilicon.

    - The Mission Possible Partnership (MPP) has set out clear pathways for steel and aluminium production to decarbonise by 2050,[185] which together with reductions in demand for primary materials, could reduce cumulative emissions from steel and aluminium by 60%, from around 15.5 $GtCO_2e$ to 5.5 $GtCO_2e$.

    - For polysilicon, the drivers of emissions are the heavy use of electricity (typically about 160 kWh per kg of polysilicon) and carbon intensity of the electricity used.[186] Production is currently dominated by coal-heavy regions in China, leading to emissions of over 800 gCO_2 per kWh. However, this will fall as the Chinese grid decarbonises and could be rapidly reduced if polysilicon manufacturers use dedicated renewable electricity resources, potentially cutting the emissions intensity of polysilicon production from 200 tCO_2e per tonne of polysilicon to below 5 tCO_2e.

Such actions together, could reduce cumulative emissions to around 16 $GtCO_2e$ between 2022-50. On an annual basis, this would be around 0.5 $GtCO_2e$ as compared to 41 $GtCO_2e$ each year from today's fossil fuel-based energy system.

Even without strong policy, the cumulative emissions required to build a net-zero emissions economy will be minimal compared with the annual emissions produced from today's fossil fuel-based system (at most 35 $GtCO_2e$ cumulatively to 2050, versus over 41 $GtCO_2e$ *each year*).

182 Concrete was not included in the analysis in Chapters 1 and 2, as overall demand from the energy transition would be trivial when compared to demand from construction. However, for completeness emissions from cement and concrete production are included here, given the volumes of concrete required for wind, nuclear and hydropower.

183 Secondary materials typically have much lower emissions intensity than primary materials: for example, recycled aluminium has an emissions intensity of around 0.6 tCO_2e/tonne of aluminium, vs. around 15.7 tCO_2e for primary aluminium.

184 The remaining carbon budget from the start of 2020 onwards, to have a 50% chance of remaining under 1.5°C of warming, was 500 $GtCO_2$. Removing two-and-a-half year's worth of carbon dioxide emissions of around 40 $GtCO_2$ p.a. yields the remaining 400 $GtCO_2$. See Table SPM.2 in IPCC (2021), *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report.*

185 Mission Possible Partnership (2022), *Making net-zero steel/aluminium possible.*

186 Hallam et al. (2022), *A polysilicon learning curve and the material requirements for broader electrification with photovoltaics by 2050.*

But a combination of voluntary commitments, carbon pricing, green procurement and strong regulation should also be used to drive dramatic and rapid emissions reductions and are likely to result in cumulative emissions far below those based on today's emissions intensities.

4.2 Material quantities, land use, and biodiversity

Land use change is a key component of local impacts from mining. Extraction of mineral ores leads to changes in local land use, the movement of large amounts of rock and the production of large volumes of tailings, and therefore has knock-on impacts on local ecosystems and biodiversity.

Producing minerals and materials will require moving large amounts of earth and rock to extract ores from which refined minerals and materials can be produced. The total amount of this material movement depends on:

- **The total volume of each final product or mineral** to be used – for example, the energy transition could need around 5,000 Mt of steel between 2022–50, which is 250 times the cumulative 20 Mt of pure lithium required for batteries.
- **The amount of ore required per tonne of pure mineral**, where, for instance, copper ores produce only about 0.6% of elemental copper compared with 25% of elemental aluminium in bauxite [Exhibit 4.3].
- **The amount of rock/earth which might need to be shifted** to extract a tonne of ore, which varies hugely between materials but also between specific sites and depends on the approach to mining (namely, underground as opposed to open-pit mining).

EXHIBIT 4.3

Ore grades and waste rock production drive differences in environmental impacts from the materials production process

Materials and associated ore grades and total material moved

[1] For hard-rock mining of lithium.

SOURCE: Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes.*

The total resulting requirement for earth/rock movement, at up to 13 billion tonnes each year, is the same order of magnitude as the material movement required for the fossil fuel-based system [Exhibit 1.10].

However, this amount could be significantly smaller by reducing primary material requirements through technical efficiency and recycling, or adopting less waste-generating extraction approaches,[187] and would decline significantly after mid-century once the new energy system has been built and high levels of recycling are reached across most materials.

Movement of earth and rock in itself has only a minimal effect on carbon emissions: waste rock and tailings produced by mining do not move very far – at most a few kilometres – and therefore at a global scale, associated emissions are low. The crucial concern is the local impact of tailings and mining waste on land use and biodiversity, and whether it has adverse effects on local ecosystems – especially when not stored and managed responsibly.

The total land use associated with today's mining operations is quite small. Best estimates using satellite imagery attribute total land area of 101,600 km^2 to mining – an area roughly the size of Iceland and less than 0.1% of global habitable land.[188]

This land requirement is a similar order of magnitude to that required for fossil fuel extraction, with oil and gas production in North America estimated to require about 90,000 km^2 of land.[189]

Increased requirements for iron ore, bauxite and copper ores in coming decades (from both the energy transition and other sources of demand) are likely to account for the vast majority of future land requirements, and could increase mining land use by 5,500–12,000 km^2 in future by 2050,[190] a 5–12% increase above current levels.

But even today's total land mining land footprint is only 1/500th of the land devoted to agriculture, and the additional land required to support mining in coming decades would be about 1/5000th of agricultural land. Not surprisingly, therefore, mining plays only a very limited role in driving direct deforestation and other forms of biodiversity loss:

- International Resource Panel estimates suggest that the direct impact of metal extraction accounts for less than 1% of global biodiversity loss, with the vast majority of loss being driven by agricultural crops and pasture [Exhibit 4.4, LHS].[191]
- Another recent study estimates that between 2005–2013 annual deforestation associated with cattle farming for beef averaged 2 million km^2 per annum,[192] compared with estimated annual deforestation of around 700 km^2 per annum deriving from mining, with coal and gold mining (both unrelated to energy transition metals) the biggest drivers of this loss.[193]

187 See e.g., Valenta et al. (2023), *Decarbonisation to drive dramatic increase in mining waste – Options for reduction.*

188 Not all of this land area is for metals mining: coal mining activities account for 5,000 mines out of the 35,000 considered in this analysis. Maus et al. (2022), *An update on global mining land use.*

189 As of 2012. Calculated based on an average rate of 2,000 km^2 of land use for every 50,000 wells drilled between 2000–2012 in North America. Allred et al. (2015), *Ecosystem services lost to oil and gas in North America.*

190 Murguía (2015), *Global area disturbed and pressures on biodiversity by large-scale metal mining.*

191 International Resource Panel (2019), *Global resource use.*

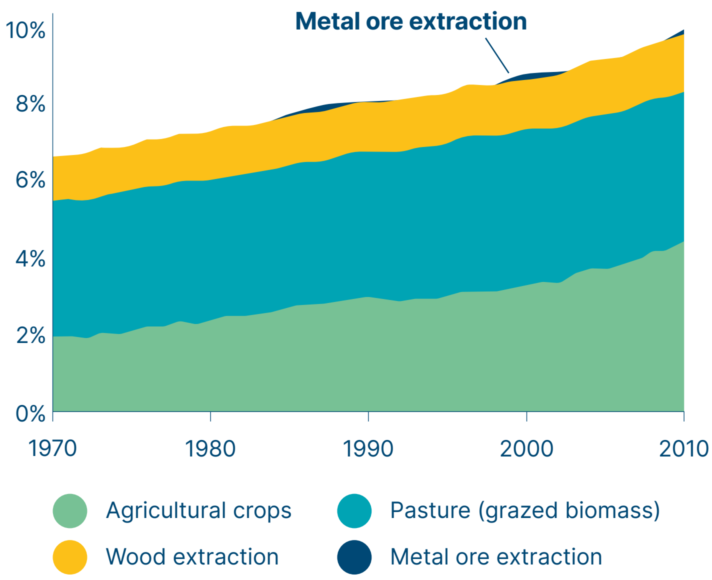
192 ETC (2023), *Financing the transition: Supplementary report on the costs of avoiding deforestation;* Pendrill et al. (2019), *Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition.*

193 WWF (2023), *Extracted forests.*

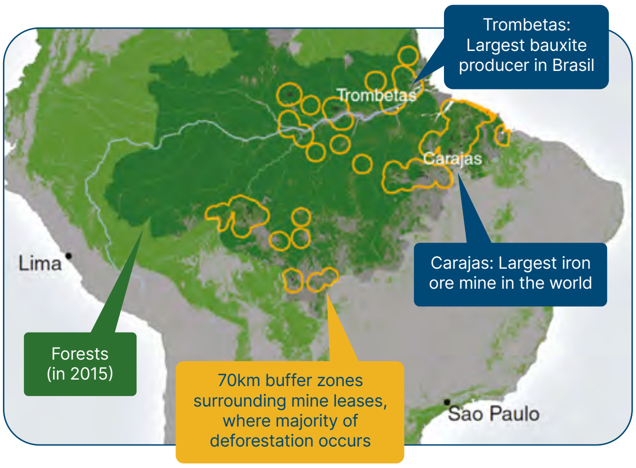
EXHIBIT 4.4

Direct biodiversity impacts from mining are on a much smaller scale relative to other existing systems, but indirect impacts on deforestation are a cause for concern

Global biodiversity loss due to land use of resource extraction¹
% of global species loss



Areas of Amazon rainforest surrounding mine leases are most impacted by indirect deforestation



In total, **indirect mining-induced deforestation in buffer zones has been 12 times greater than that occurring exclusively within land leased for mining,** and caused 9% of all deforestation within Brazil's Amazon rainforest between 2005–15.

¹ Does not include indirect impacts on land use, for example the development of roads for mining sites which then lead to other economic activities requiring deforestation.

SOURCE: International Resource Panel (2017), *Assessing Global Resource Use*; Sonter et al. (2017), *Mining drives extensive deforestation in the Brazilian Amazon (re-used and adapted with permission under the CC BY 4.0 license)*; Sonter et al. (2018), *Mining and biodiversity: key issues and research needs in conservation science.*

It is important to recognise however that the expansion of mining can have significant indirect effects on deforestation and biodiversity loss if the development of a mine site in a forest requires the construction of road and other infrastructure which opens up forests for further economic activity and deforestation.[194]

A study of the Brazilian Amazon rainforest estimates that mining-induced indirect deforestation occurs at a rate twelve times larger than that occurring purely on mining land leases alone [Exhibit 4.4, RHS].[195] At a global scale, estimates suggest that mining could have led to induced deforestation over up to 760,000 km^2 through indirect or induced deforestation, or roughly 38,000 km^2 each year (compared with total global deforestation of around 100,000 km2 each year).[196,197] However, the vast majority (>70%) of mining deforestation is driven by coal, where impacts should decrease in coming decades, and gold, which is not relevant to the energy transition.[198] Further, the vast majority of aluminium and steel demand is from non-energy transition sources, and these two materials account for another 15% of deforestation. Demand for metals from the energy transition is unlikely to be the dominant driver of additional deforestation - but action to reduce deforestation and biodiversity loss from mining is still vitally important.

In the context of potential future expansion of mining for energy transition materials, a large proportion of global reserves for copper, nickel and other key materials are located in sensitive ecosystems and areas of high biodiversity.[199]

194 Illegal mining is also a concern: in cases where property rights are not well documented and enforced, deforestation can also take place as illegal mine sites are expanded.

195 Sonter et al. (2017), *Mining drives extensive deforestation in the Brazilian Amazon;* Sonter et al. (2018), *Mining and biodiversity: key issues and research needs in conservation science.*

196 Our World in Data (2021), *Forests and deforestation*; UN Food and Agriculture Organisation (2020), *Global forest resources assessment.*

197 WWF (2023), *Extracted Forests.*

198 Ibid.

199 Giljum et al. (2022), *A pantropical assessment of deforestation caused by industrial mining;* Sonter et al. (2018), *Mining and biodiversity: key issues and research needs in conservation science*; Sonter et al. (2020), *Renewable energy production will exacerbate mining threats to biodiversity.*

In response it is important both to focus strongly on the actions described in Chapter 2, which can reduce demand for primary materials, and on any potential to source minerals from less sensitive locations.

4.3 Local toxicity and pollution impacts

While the movement of materials, even in the large quantities shown in Exhibit 1.10, does not in itself have necessarily large environmental impacts, mining can also produce large local pollution – especially if waste products are not managed and disposed of safely.

The mining process can lead to pollution across multiple stages, from excavation to transport and final processing. This can lead to a range of impacts, such as:

- **Effluents discharge**, which can pollute local land and water bodies.
- Generation of large volumes of **particulate matter**, worsening local air quality.
- **Eutrophication and ecotoxicity** impacts in water bodies, reducing the availability of clean water and reducing the viability of local ecosystems.
- **Leakage or collapse from tailings** storage, which can lead to very high concentrations of toxic reagents or heavy metals in local land and water.

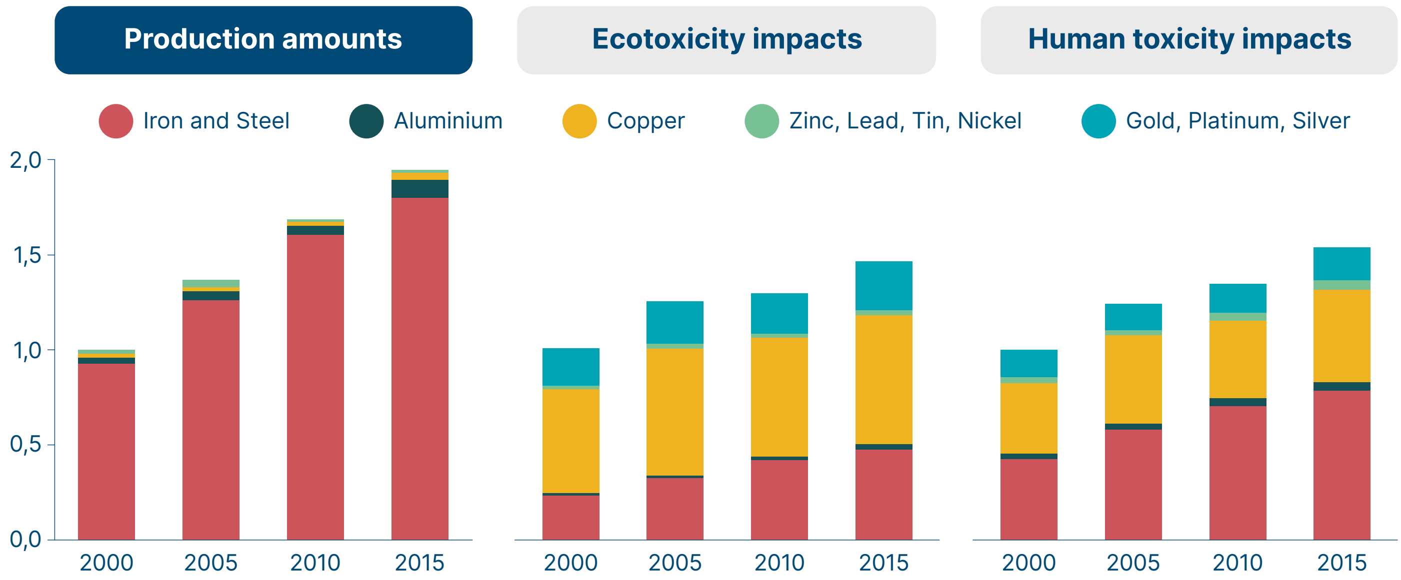
The energy transition material, which tends to raise the most significant concerns from an ecotoxicity and pollution perspective, is copper – where future mining production could nearly double from current levels.[200] Analysis by the International Resource Panel shows that even though copper made up less than 5% of global metals production between 2000–2015, copper mining and processing made up the majority of ecotoxicity impacts and a large share of human toxicity impacts over this period [Exhibit 4.5].

EXHIBIT 4.5

Copper production has a disproportionately large impact on pollution relative to its share of total material production

Metal production amounts and toxicity impacts of metal mining and processing

Normalised such that 2000 = 1



SOURCE: International Resource Panel (2019), *Global resources outlook*.

200 The impacts of gold mining are also very significant, but gold has very little relevance to the energy transition. Copper production could reach over 40 Mt per annum, see S&P Global (2022), *The future of copper;* BNEF (2022), *Global copper outlook 2022-40.*

Much of this can be linked to two key factors:

- **Copper ore grades** have fallen to very low levels (about 0.6% globally on average),[201] leading to large volumes of rock moved for every ton of copper extracted – copper produces around one-third of all mining tailings currently.[202]

- Copper mining produces very large volumes of **sulphidic mining tailings**:

  - Sulphidic mining tailings lead to the key issue of Acid Mine Drainage, whereby sulphide minerals are exposed to water and oxygen, forming sulphuric acid.

  - The sulphuric acid then dissolves heavy metals (present in the tailings from the wider mining process), and leakage of these can lead to contaminated water, death of aquatic life, and renders local water sources unusable for human consumption or agriculture.

There are also other local environmental impact concerns for mining of other materials, such as toxic waste production in rare earth element mining,[203] or generation of very large volumes of highly-alkaline bauxite residues (known as "red mud") during processing of bauxite into alumina. Mining disasters, notably tailings dam collapses, which often take place in cases where there are poor environmental standards and a lack of investment and care taken for appropriate waste management, can exacerbate local pollution significantly.[204]

Beyond mining, processing and refining can also yield substantial local pollution impacts if not carried out responsibly. Smelting and refining of copper releases large amounts of sulphur dioxide, leading to acid rain which damages local trees, crops and buildings.[205] Use of acids in hydrometallurgical (water and solvent-based approaches) processing/refining of rare earth elements, or in the production of cobalt or nickel sulphate, also leads to large volumes of chemical waste, which can have significant local pollution impacts if not disposed of appropriately.[206] Finally, pyrometallurgy (heat-based approaches) in copper or nickel refining can also lead to local particulate emissions if not appropriately managed, impacting local air quality.[207]

Given the disproportionate local pollution impacts arising from copper mining, particular attention should focus on:

- Reducing primary material requirements for copper. Reducing primary copper demand by increasing circularity could lead to 100 billion tonnes less tailings and waste rock produced between 2022–50.[208] This would save on material processing, along with its associated emissions and water use, and would avoid moving this volume of rock into tailing ponds for storage, along with any potential local environmental impacts from, e.g., tailings storage or acid mine drainage.

- Reducing local pollution impacts for every tonne of mined copper, by focusing on highest-quality resources and driving productivity improvements at mine sites, and ensuring appropriate waste management.

201 Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes.*
202 Ibid.; ICMM (2022), *Tailings reduction roadmap.*
203 Ali (2014), *Social and environmental impact of the rare earth industries;* BBC Future/Tim Maughan (2015), *The dystopian lake filled by the world's tech lust.*
204 See e.g., New York Times (2019), *Brumadinho dam collapse: A tidal wave of mud.*
205 Izydorczyk et al. (2021), *Potential environmental pollution from copper metallurgy and methods of management.*
206 Zapp et al. (2022), *Environmental impacts of rare earth production;* Mistry et al. (2016), *Life cycle assessment of nickel products;* Rinne et al. (2021), *Life cycle assessment and process simulation of prospective battery-grade cobalt sulfate production from Co-Au ores in Finland.*
207 Izydorczyk et al. (2021), *Potential environmental pollution from copper metallurgy and methods of management;* Nickel Institute/Nickel Magazine (2014), *The life cycle of nickel.*
208 Efficiency and recycling measures could reduce cumulative primary copper demand from the energy transition between 2022-2050 from 525 Mt down to 315 Mt. Assuming a waste rock and tailings production of around 500 tonnes per tonne of copper, this would amount to roughly 100 billion tonnes of waste rock that would not be produced. Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes.*

4.4 The impact of water consumption in mining

Mining for metals consumes around 4 billion m^3 of water each year – around half of what is consumed by coal mining [Exhibit 4.6], and about 0.1% of global agricultural water consumption.

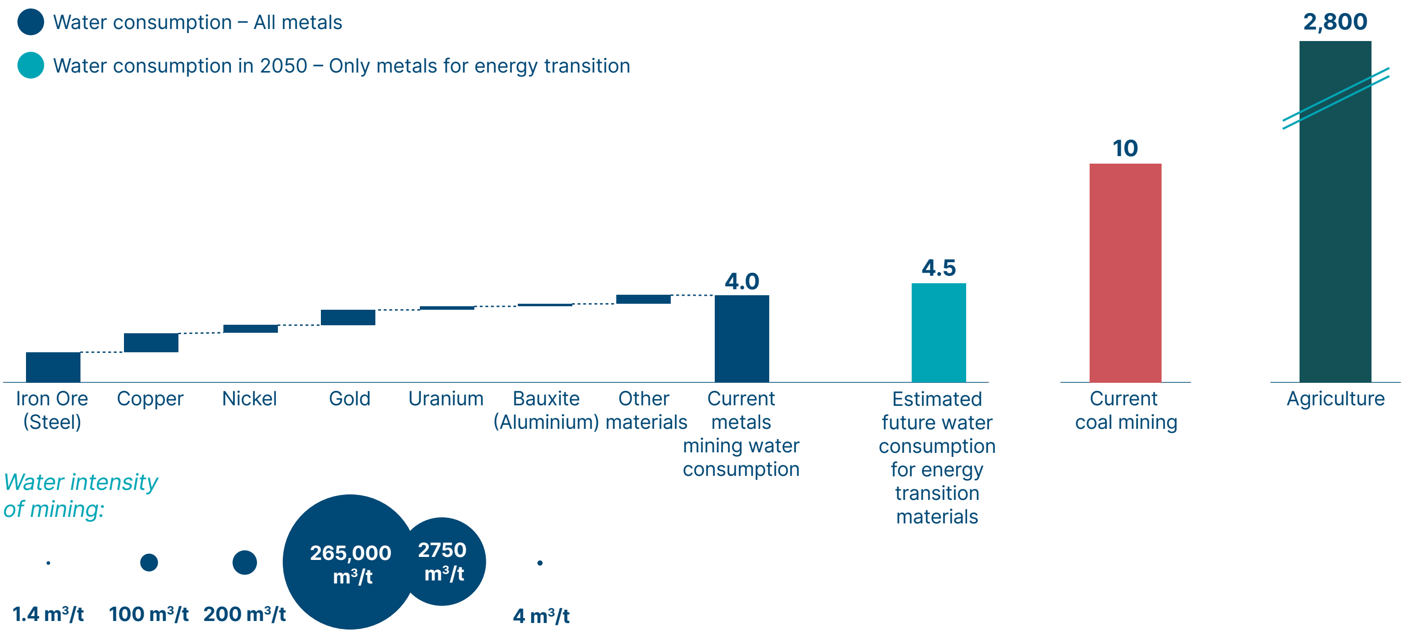
Water use to mine metals for the energy transition could reach a similar level (around 4.5 billion m^3) by 2050, reflecting the high water intensity requirements for some production materials – notably copper, nickel and lithium.[209] Even with this increase, new water use for materials mining will still be a minute proportion of total agricultural water use.

However, it is important to note that mining often takes place in very arid or water-stressed areas. For example, copper mining in northern Chile, or the mining of iron ore in Pilbara in north-western Australia – in both cases, local water consumption from mining is significant and can exacerbate local water stress [Exhibit 4.7].[210] One study finds that there are several regions, mainly in Australia and South America, where mining water consumption exceeds natural water availability for a regional river basin.[211]

EXHIBIT 4.6

Water consumption for metals mining could rise in future, driven by energy transition – but scale is far below agriculture

Annual water consumption[1] from metals mining
Billion m^3



NOTE: [1] Water consumption is water that is taken from a source and is not returned to the source. [2] At current water intensities.

SOURCE: Systemiq analysis for the ETC; Meissner (2021), *The impact of metal mining on global water stress and regional carrying capacities – A GIS-based water impact assessment*; Our World in Data (2017), *Water use and stress*; IEA (2016), *Water-Energy Nexus.*

209 Water intensity of lithium extraction varies depending on whether it is produced from brines or hard rock mining, but can be up to 1000 m^3 per tonne of contained lithium in the case of brines. IEA (2021), *The role of critical minerals in clean energy transitions;* Minviro/Livent (2022), *Growing responsibly – 2021 Sustainability Report.*

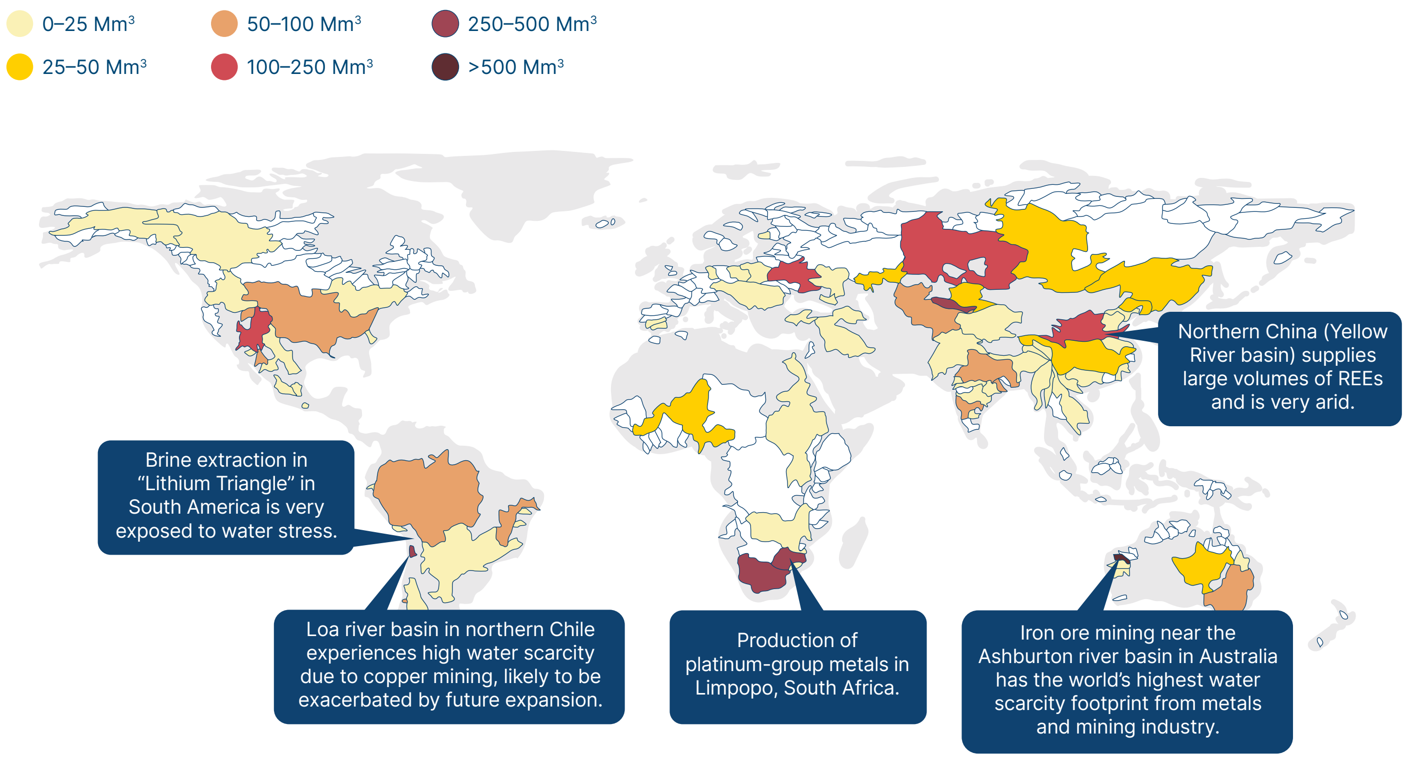
210 Meissner (2021), *The impact of metal mining on global water stress and regional carrying capacities.*

211 Ibid.

EXHIBIT 4.7

Mining can exacerbate water stress and needs careful management on a local level

Water scarcity footprint of mining, by river basin
Million m³ p.a.



NOTE: Water scarcity footprint is a measure of water use that weights water consumption using a region-specific water scarcity index.

SOURCE: Meissner (2021), *The impact of metal mining on global water stress and regional carrying capacities (re-used and adapted with permission under the CC BY 4.0 license).*

Climate change itself, moreover, may exacerbate water stress in many regions and/or increase the need for effective water management as precipitation becomes more variable even in regions when net precipitation increases.

It is important, therefore, for the mining industry and governments to focus on actions which will minimise adverse effects on water supply, both through water management strategies and innovation to reduce water needs (e.g., through new extraction methods such as Direct Lithium Extraction).[212]

4.5 Impacts on local communities and society

Mining can often have strong positive impacts on economic growth, export opportunities, and tax revenues. Mining projects can bring local employment opportunities, both during construction and operation, and well-designed projects with positive community engagement can leave strong, lasting development benefits at a local and national level.[213] The increase in material demand for the energy transition therefore presents significant opportunities for lower income countries, which account for a large share of global material resources.[214]

212 Government of Western Australia/Department of Water (2013), *Pilbara regional water supply strategy;* Comision Chilena del Cobre/Ministerio de Mineria (2017), *Water consumption forecast in copper mining 2017-28.*

213 As a crude measure, mining contribution to GDP can be 10% – World Bank (2023), *Mineral rents (% of GDP).* See also ICMM (2022), *Mining contribution index.*

214 See e.g., World Bank (2019), *Climate-smart mining initiative;* Natural Resource Governance Institute (2022), *Triple Win: How mining can benefit Africa's citizens, their environment and the energy transition.* See also Chapter 3, Exhibit 3.6 of this report for estimated revenues from five key energy transition materials.

However, in certain cases, historically many of the benefits of mining have been distributed unequally between companies, governments and communities, and across regions and income groups, with far fewer increases in income and wellbeing accruing to local populations in mining towns.[215] This is especially the case for Indigenous peoples – estimates suggest a large proportion of future resources of energy transition metals are located near or on Indigenous lands,[216] highlighting the need for strong and appropriate engagement and respect for community rights [see also Box I].

Further, there are a wide range of issues that can arise from poorly regulated and informal mining, with strong costs for mining communities:[217]

- **Local air, water and land quality is degraded**, negatively impacting local ecosystems and the health of the population.[218]
- Workers can be made to work in very poor conditions with **human rights abuses, low standards for health and safety**, and in some cases use of **child labour**.[219]
- **Corruption and tax avoidance** can become major concerns, preventing the economic benefits from mining from accruing to legitimate recipients.[220]

The disruptive impacts of resource extraction on local populations, when not managed in a sustainable and responsible manner, are varied and substantial.

In order to address these impacts on local communities, as well as the environmental impacts outlined above, there must be a concerted effort across the entire mining industry to become more sustainable and responsible.[221]

Further, when thinking about the impacts of mining on natural resources and the environment, it is important to consider that whilst on a global scale impacts may be small relative to other sectors and systems (e.g., the land requirements for mining compared to the agricultural system), mining can have very concentrated impacts on local communities and ecosystems. The cost of many of these impacts would fall almost exclusively on local communities impacted by mining, alongside other considerations around corruption, working conditions, consent and more.

If not managed well, there could be a significant imbalance between the global benefits of decarbonisation, traded off against highly-concentrated local costs of increased mining.

Only by making progress on these fronts can the mining industry build trust and maintain the social license to operate required to rapidly expand production over coming years.

4.6 Key areas of focus to ensure sustainable and responsible materials for the energy transition

Looking across the environmental and social challenges outlined throughout Chapter 4, five key priority areas stand out:

- **Emissions intensity of steel and aluminium:** The combination of widespread use and the emissions-intensive production leads to these two materials dominating the global warming impacts of materials for clean energy technologies [see also Exhibit 4.2]. However, there is strong potential for these two materials to decarbonise by mid-century provided necessary actions are taken by industry, policymakers and investors.[222]
- **Reducing use of primary copper:** Mining for copper faces continuous declines in ore grades, which have fallen from over 2% in the early 1900s down to around 0.6% currently – and could fall below 0.5% in coming decades.[223] This leads to higher energy and water consumption for every tonne of copper produced, along with greater volumes of waste

215 Loayza and Rigolini (2016), *The local impact of mining on poverty and inequality: Evidence from the commodity boom in Peru;* OECD (2019), *Enhancing well-being in mining regions: Key issues and lessons for developing indicators.*
216 Owen et al. (2023), *Energy transition minerals and their intersection with land-connected peoples.*
217 IEA (2022), *Why is ESG so important to critical mineral supplies, and what can we do about it?*
218 OECD (2019), *Enhancing well-being in mining regions: Key issues and lessons for developing indicators.*
219 Business & Human Rights Resource Centre (2021), *Transition Minerals Tracker: 2021 Analysis;* Mancini et al. (2018), *Social impact assessment in the mining sector: Review and comparison of indicators frameworks.*
220 WEF/Helen Clark (2023), *Does the potential for corruption in the mining sector threaten a just energy transition?;* International Monetary Fund (2021), *Tax avoidance in sub-Saharan Africa's mining sector.*
221 Two examples of best-in-class performance could be the new Quellaveco copper mine (discussed in Box H), or Anglo American's Unkli platinum mine – the only mine to have currently successfully completed an independent audit meeting the Initiative for Responsible Mining Assurance's IRMA75 achievement level.
222 Mission Possible Partnership (2022), *Making net-zero steel possible/Making net-zero aluminium possible.*
223 Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes;* S&P Global (2022), *The future of copper; BNEF (2023), Transition metals outlook.*

rock and tailings. Reducing primary copper use through substitution or recycling, and making copper mining more efficient and productive, to reduce waste, emissions and water per ton produced is key.

- **Emissions intensity of battery materials:** High embedded carbon emissions are a major risk for the supply of lithium and nickel – especially as future mining and processing approaches could be more emissions-intensive than the current standard.[224] Here the focus should be on decarbonising mining and manufacturing in coming years, whether through renewable power-purchase agreements or by wider grid decarbonisation, or by focusing on lower-carbon extraction methods (e.g. DLE).

- **The supply of cobalt from the DRC** has been associated with high levels of conflict and armed violence, partly linked to control of natural resources in the mining-heavy eastern regions of the country.[225] A major area of focus of such concerns is the artisanal and small-scale mining (ASM) sector. These mines often operate with much lower health and safety standards, make use of forced or child labour, and take little or no measures to mitigate impacts on workers or the local environment.[226] Innovation to shift away from cobalt, as has already happened in recent years [Exhibit 2.10], can help reduce demand and mitigate risks associated with supply from the DRC, whilst improved supply chain transparency and traceability can provide stronger consumer confidence in responsible cobalt supply.

- **Solar PV and polysilicon production:** Polysilicon production across China is predominantly reliant on coal-fired power stations, leading to highly emissions-intensive production – roughly double what domestic production in the USA or Germany would be.[227] In addition, around 30% of global polysilicon production takes place in the Chinese region of Xinjiang, where concerns have been raised about human rights issues both coal mining and polysilicon production.[228] Diversifying production of polysilicon can help both reduce the carbon intensity of production and avoid supply linked to human rights issues.[229] Stronger supply chain traceability can also help monitor impacts throughout solar supply chains.

4.7 Actions required to make material supply more sustainable and responsible

Sustainable and responsible materials supply requires mining companies to take action to minimise adverse impacts across three dimensions:

- **Reducing the life-cycle emissions** associated with both extraction and processing of materials.

- **Managing and mitigating local environmental impacts.**

- **Avoiding negative social, political and economic externalities.**

Miners must strive for operational excellence across all of the three areas of action. Many mining companies already exhibit best-in-class approaches to manage and mitigate environmental and social impacts. However, in many cases particular mine sites or companies perform well below average, let alone to a high level. Companies should prioritise learning and implementing practises from top performers across the topics outlined below.

These impacts can be reduced by first, reducing the amount of primary materials required for the energy transition through circular levers (as outlined in Chapter 2), and then by reducing impacts for every ton of primary material that needs to be produced – the focus of this chapter.

224 IEA (2021), *The role of critical minerals in clean energy transitions;* EIT Raw Materials/Minviro (2021), *Exploring the environmental impact of batteries and EV motors using LCA.*
225 See e.g., The Economist (2022), *The world should not ignore the horrors of eastern Congo.*
226 Ibid.; Amnesty International/AfreWatch (2016), *This is what we die for: Human rights abuses in the DRC power the global trade in cobalt;* World Economic Forum (2020), *Making mining safe and fair: Artisanal cobalt extraction in the DRC.*
227 IEA (2022), *Special report on solar PV global supply chains.*
228 The Breakthrough Institute (2022), *Sins of a solar empire;* Murphy and Elimä/Sheffield Hallam University (2021), *In broad daylight.*
229 See e.g., IEA (2022), *Special report on solar PV global supply chains.*

Importantly, actions to reduce environmental impacts must address both supply routes: whilst scaling recycled supply can easily help address, for example, lower carbon intensity requirements, there is a limit to how far secondary supply can go (as outlined in Chapter 2). It is thus imperative to also ensure that primary supply of materials is made as sustainable as possible, and that both routes are incentivised as effectively as possible. Chapter 2 sets out how to incentivise increased recycling; this chapter focuses on ensuring sustainable and responsible primary supply. A significant body of work and initiatives exists, from across the public and private sector, to promote and implement sustainable and responsible mining and materials supply chains. This includes:

- **The Extractives Industries Transparency Initiative (EITI):** membership requires countries to commit to disclosing information regarding their extractive industry value chains, including how extraction rights are awarded, how revenues make their way through government, and how they benefit the public.[230] To date, more than 50 countries have agreed to a common set of rules, aimed at promoting transparency and reducing corruption in the sector.

- **The World Bank's Climate Smart Mining Initiative:** aims to help resource-rich lower income countries benefit from the increasing demand for minerals and metals, while ensuring the mining sector minimises environmental and climate footprints.[231] The initiative includes strong governance and regulatory frameworks, multi-stakeholder engagement, and aligns to the Sustainable Development Goals and the Paris Agreement.

- **The International Council on Mining and Metals (ICMM):** an industry body which aims to enhance the contribution of mining and metals to sustainable development and social progress within local communities and entire countries.[232] ICMM's Mining Principles define the good practice environmental, social and governance requirements of company members through 39 standards.

- **Towards Sustainable Mining (TSM):** An initiative established by the Mining Association of Canada and adopted by a wide range of other country mining associations, TSM requires members to undergo assessment and independent validation across 30 indicators of environmental and social performance.[233]

- **The Initiative for Responsible Mining Assurance (IRMA):** a coalition of NGOs, mining companies, industrial consumers, local community and labour representatives. IRMA has launched a Standard for Responsible Mining, a global certification program for industrial-scale mining sites, covering four core principles of business integrity, social responsibility, environmental responsibility, and planning for positive legacies.[234]

In response to growing momentum across the whole value chain for sustainable and responsible mining, a large number of voluntary standards organisations have also been established, developing criteria for mining companies and sites to adhere to.[235]

This report provides a high-level summary of the actions and investments needed by mining companies for sustainable and responsible mining, but does not go into detail on the specific technologies or criteria, recognising that these are covered extensively by various other organisations. Instead, it provides discussion of how policymakers, regulators, the private sector, and financial institutions can create the right foundations to enable and accelerate progress in sustainable and responsible mining.

Mineral supply chains are long and complex, covering not just mining companies but also many important downstream players, notably smelters and refiners, and end-purchasers of products that contain materials [Exhibit 4.8]. There are also a range of important cross-cutting actors: governments, civil society, voluntary standards and certification bodies, and investors.

230 EITI (2023), *Our mission*.
231 World Bank, Climate-Smart Mining Facility (2020), *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*.
232 ICMM (2023), *Who we are*.
233 Towards Sustainable Mining (2023), *About*.
234 IRMA (2018), *Standard for responsible mining*.
235 See e.g., Copper Mark, Aluminium Stewardship Initiative, Responsible Steel, or SBTi initiatives.

EXHIBIT 4.8

Key actors across mineral and clean energy technology supply chains

1. Miners

- Carry out extraction of mineral ore and some initial processing.
- Responsible for operations at mine site, energy use, labour rights, working conditions etc.
- Can be large established international miners, mid-size companies or artisanal miners (where operations have less mechanisation, often highly labour-intensive).

2. Traders, Exporters

- Traders and exporters purchase commodities in return for cash. Local trading houses and exporters typically serve small-scale operations (large-scale miners often go direct to smelters and refiners).
- Responsible for providing proof of payments and taxes, mineral origins, and import/export information.
- Large international commodity traders carry out transportation and transformation of commodities across countries.

3. Smelters and refiners

- Point of transformation, where mineral or commodity is processed to reach commercial-market quality product.
- High likelihood of purchased minerals/commodities being physically mixed at this stage, causing problems for traceability and impact monitoring.

4. Manufacturers

- Refined and processed minerals enter consumer market as small parts of specific components (e.g. batteries).
- Manufacturers can use purchasing power to pressure suppliers to drive higher standards.

5. Purchasers

- Consumers, installers, operators, governments all make purchasing decisions for clean energy technologies.
- Purchasing power can be used to pressure suppliers to drive higher standards.

6. Recyclers

- Process end-of-life products, scrap into recycled secondary supply of materials.
- Can cover logistics of recycling, and own/operate smelting and refining capacity.

7. Key cross-cutting players

Civil Society

Key stakeholder for new mining, manufacturing and renewables projects – civil society consent will enable the energy transition to proceed at pace and scale.

Governments

- Impose domestic and/or international regulations that miners and manufacturers must adhere to.
- Laws can cover environmental and social standards for operations, due diligence reporting requirements, local content requirements and more.
- Some international collaboration initiatives via e.g. the OECD Due Diligence Guidance for Responsible Supply or the Extractive Industries Transparency Initiative.

Voluntary standards and certification bodies

- Very wide range of standards currently existing, covering different mine sites, mining companies, commodities and industries.
- Set out requirements for adherence, carry out audits and due-diligence as trusted third parties.

Investors and Markets

- Investors provide capital to miners, smelters and manufacturers. Markets serve to connect physical producers with financial players, providing pricing, options and futures contracts and other services – including, for example, proposed "passports" that provide transparency around key sustainable and responsible sourcing criteria.
- Can act as enforcement mechanism for companies to adhere to regulation and/or voluntary standards and reporting mechanisms.
- Multilateral development banks often play a key role in: a) de-risking finance for projects in lower-income countries; b) driving adoption of new regulations and standards.

Creating a concerted and widespread shift towards sustainable and responsible mining requires the incentives and signals from all parts of the mining supply chain to be aligned.

A crucial aspect of ensuring environmental and social impacts are minimised is through regulations in key mining jurisdictions: these must be both robust and well enforced, with local regulators having the sufficient expertise, capacity and funding to verify sustainable and responsible mining operations.

This section covers:

- Actions **mining companies** can take to make mining more sustainable and responsible, drawing on existing initiatives.
- Recommendations for **policymakers, regulators, and the private sector** to enable and promote sustainable and responsible mining.
- A deep-dive on **voluntary standards** within mining and recommendations for improvement.

4.7.1 Actions for mining companies to make mining more sustainable and responsible

① Decarbonising the mining sector and value chain

As outlined in Section 4.1, mine-site and downstream emissions together account for around 11% of global GHG emissions.

In addition to the emissions that will be avoided from a gradual elimination of fossil fuel extraction, it is also possible to reach net-zero within the mining and downstream sectors (i.e., steel and aluminium production, two of the key "hard-to-abate" heavy industry sectors) – but this will require strong action from both governments and businesses.[236]

This section summarises some of the key levers for decarbonisation within mining; separately, see the Mission Possible Partnership's sector transition strategies for industry-backed net-zero pathways for some of the hard-to-abate sectors reliant on mining, including steel and aluminium.[237]

Key actions to decarbonise the mining sector:

- **Transition to clean electricity:** for the average mine site, around half of energy consumption is electricity.[238] Mining companies can ensure they are using clean power by developing on-site renewable energy generation capacity, and through corporate renewable power purchase agreements.
- **Focus on highest-quality deposits:** mining ore grades that are only fractionally higher in absolute terms (e.g., going from 1% to 1.05% ore grade for copper) can deliver disproportionate benefits in reducing life-cycle emissions for end-products.
- **Switch to clean heavy vehicles:** diesel mining vehicles have typically been the only option for transporting the size and weight of materials around mine sites, and can account for anywhere between 30% and 80% of direct emissions.[239] Diesel fleets can be replaced with battery-electric and hydrogen trucks which, when combined with clean electrification, can reduce direct mine site emissions. Most urban zero-emissions trucks are expected to reach total cost of ownership parity between 2025–34, with long haul following shortly after.[240] Mining companies can develop strategic alliances with OEMs of such vehicles and should invest ahead of time in the enabling on-site charging infrastructure.
- **Invest in energy efficiency:** there are a number of innovations, including digitalisation, data and analytics, and technological improvements which are driving more precise and efficient mining operations, therefore reducing energy use as well as local environmental impacts. For example, new approaches to the extraction and purification of natural graphite, using lower temperatures and less corrosive acids, can help reduce its embedded carbon emissions by 95% relative to synthetic graphite, which is made from fossil fuels.[241]
- **Neutralise residual emissions:** for any remaining residual or hard-to-abate emissions, mining companies should neutralise these using high-quality carbon removal offsets to achieve net-zero emissions.[242] Crucially, this should not be a substitute for deep decarbonisation efforts and any "beyond value chain mitigation" should be additional, not instead of, absolute emissions reductions which are technically and economically feasible (as per the points above).

236 See e.g., ETC (2022), *Australian Industry ETI – Phase 2: Setting up industrial regions for net zero;* IFC (2023), *Net-Zero Roadmap for Copper and Nickel;* CEFC/MRIWA (2023), *Mining in a low emissions economy.*
237 Mission Possible Partnership (2022), *Making net-zero steel possible/Making net-zero aluminium possible.*
238 ICMM (2023), *Mitigating GHG emissions and building resilience.*
239 ICMM (2022), *Collaboration for innovation: Accelerating the implementation of zero emissions vehicles for the mining and metals industry.*
240 Mission Possible Partnership (2022), *Making Zero-Emissions Trucking Possible.*
241 See e.g., The Economist (2023), *Firms search for greener supplies of graphite for EV batteries.*
242 See e.g., ETC (2021), *Mind the Gap* for a detailed discussion on the need for removals and conditions for their use by companies.

Mining operations are often located in climate-vulnerable areas, making infrastructure exposed to physical risks (e.g., floods and storms), and business operations vulnerable to the effects of climate change (e.g., water scarcity, transport and logistics disruptions).[243] Mining companies will thus directly benefit from contributing to global decarbonisation efforts which limit warming to as close to 1.5°C as possible – and should simultaneously invest in local adaptation measures, to future-proof supply operations.

② Mitigating local environmental and nature impacts

Better mitigation and management of local environmental and biodiversity impacts is critical to the scale-up in mining for the transition occurring in a sustainable and responsible manner.

Key actions for mining companies to mitigate local environmental impacts include, but are not limited to:

Precision mining: focusing on highest-quality resources and investing in technological innovations can offer significant opportunities to reduce local environmental impacts (e.g., waste, pollution, water use). This can include precision targeting of high-grade resources and increasing the use of data science to optimise operations and trace impacts in real-time.

Improved tailings management: mining companies need to adopt a comprehensive, holistic approach across the life cycle for the safe and responsible management of tailings, including governance of tailings management (e.g., accountability for decisions, risk management), and good engineering practices which can help reduce human errors.[244] The International Council on Metals and Mining has recently published a comprehensive strategy to help mining companies reduce the volumes of tailings produced by mining.[245] This includes a range of short- and long-term solutions:

- Advanced sensing and particle sorting, to better identify which rock fragments should be kept and recovered, or rejected.
- Increased use of in-situ extraction – currently mainly used for uranium mining, but potentially also applicable to, e.g., rare earth elements, copper or nickel (although impacts on local water supply would need careful monitoring).[246]
- Preferential fracturing techniques, to ensure more targeted fracturing close to mineral grain boundaries.

Beyond this, exploring options to re-process tailings and waste rock in order to extract further valuable resources should also be explored where technically and economically feasible – as outlined for copper in Chapter 3.

Reducing freshwater consumption: There are existing efforts to reduce water consumption at mine sites, improving mine site efficiency of water use,[247] increase re-use and recycling of water, and ensure that mining companies make use of distinct water resources from local populations.[248] Such efforts require close collaboration between companies, local communities and governments to understand the different uses and needs for water in a particular basin or catchment area – and stronger use of monitoring and reporting of water consumption should be central to this. The development of water use strategies at national or regional levels for the mining sector and beyond, as has been done in Pilbara in north-western Australia and by the Chilean Copper Commission, can be highly effective.

243 IEA (2021), *The role of critical minerals in clean energy transitions;* McKinsey & Co. (2020), *Climate risk and decarbonisation: What every mining CEO needs to know.*
244 ICMM (2021), *Tailings Management: Good Practice Guide.*
245 ICMM (2022), *Tailings reduction roadmap.*
246 See e.g., CSA Global/Maxim Seredkin (2019), *Overview of in-situ recovery for non-uranium metals.*
247 Gunson et al. (2012), *Reducing mine water requirements.*
248 McKinsey & Company (2020), *Desalination is not the only answer to Chile's water problems;* The Economist (2022), *A test of whether big mining is socially sustainable.*

At the mine site, more effective water management can include:[249]

- Using desalinated water supplies.[250]
- Re-routing existing water sources, to avoid contamination and/or avoid disrupting existing uses by local communities.
- Using water from sources not suitable for local consumption but which are appropriate for certain mining processes.
- Ensuring quantity and quality of water discharges are closely controlled to minimise impacts.
- Investing in R&D and innovation to reduce water requirements across mining and processing.

Stronger nature stewardship: mining often occurs in ecologically sensitive areas and has a responsibility to protect local environments, given the sector is entirely dependent on nature to operate. Key actions should include:

- Commitment not to mine in World Heritage Sites, regardless of how rich the reserves are.[251]
- Sharing biodiversity data at mine sites to support species conservation and enable ongoing monitoring.[252]
- Becoming "stewards of nature", and helping to protect and nurture local ecosystems. Restoring degraded land in biodiversity hotspots, committing to protect forest inside or adjacent to mining leases, and implementing clear steps to mitigate biodiversity loss.[253] A crucial aspect of this is ensuring that impacts are monitored and mitigated both on and off-site for mining projects.[254]
- Engage with Taskforce on Nature-related Financial Disclosures (TNFD) pilots to develop a nature-related risk management and disclosure framework, which aims to integrate nature into decision-making.[255]
- Currently, most environmental impact assessments do not include estimates for indirect deforestation caused by new projects. Research and trials should be encouraged in order to better understand how these indirect impacts can be quantified, and in future accounted for in assessments.

Beyond these specific actions, there also exists an opportunity for mining companies to develop potential new business strategies in a more circular world, building a strategy and company identify not just around sustainable and responsible mining, but around how they operate in a circular economy. This could involve:

- **Developing circular business models to becoming "resource managers",** where provision of resources/metals is done in a more service-oriented way. This would expand operating models beyond simply mining primary materials, but could extend to the provision of secondary recycled supply, providing tracing and monitoring capabilities throughout material life-cycles, or becoming effective managers of disused mining sites and waste. By shifting to such "metals-as-a-service" and other business models there is the potential to expand the range of revenue streams available to companies – as is already being done for certain precious metals.[256]

249 For more detail see IRMA (2018), *Standard for Responsible Mining – Chapter 4.2*; ICMM (2014), *Water stewardship framework*.

250 Although energy requirements are quite high (up to 16 kWh/m³), costs have fallen to below $2/m³, providing an opportunity for expanded use of desalination where local energy, costs, and management of brine discharge permit. Eke et al. (2020), *The global status of desalination: An assessment of current desalination technologies, plants and capacity*; Shokri and Fard (2022), *Techno-economic assessment of water desalination: Future outlooks and challenges.*

251 For example, ICMM members have committed not to explore or mine in World Heritage Sites.

252 Anglo American, for example, has committed to share its data in the eBioAtlas, an initiative from the IUCN and Nature Metrics measure and track fill gaps in knowledge around conservation and biodiversity. Mining.com (2021), *Anglo commits to provide eDNA data to protect biodiversity.*

253 For example, Vale is restoring degraded areas of the Carajás National Forest and its surrounding areas in Brazil to re-establish connections between fragmented areas of forest and to protect the home of endangered species. It is planting more than 500,000 seedlings to expand the native vegetation, creating new micro-habitats for wildlife and increasing the diversity of species. World Bank (2019), *Forest-smart mining; Proteus Partners* or ICMM (2015), *A cross-sector guide for implementing the mitigation hierarchy.*

254 See e.g., Giljum et al. (2022), *A pantropical assessment of deforestation caused by industrial mining;* Sonter et al. (2020), *Renewable energy production will exacerbate mining threats to biodiversity.*

255 TNFD (2023), *TNFD Pilots.*

256 See e.g., Systemiq (2021), *Everything-as-a-Service;* Evonik (2023), *Precious metal management & recycling;* BASF (2023), *Precious and Base Metals.*

③ Managing social, political and economic externalities

The energy transition is not just a necessary route to achieve net-zero, but a necessary path to sustainable and inclusive growth and development for middle and low income countries. Achieving a just energy transition requires addressing climate change at the same time as poverty and inequality. If done right, developing a sustainable and responsible mining sector can play a key role in this – and can help achieve the societal buy-in required for mining of metals for the energy transition.

There are many factors beyond the control of mining companies which can influence how mining benefits or impacts local communities and economies, including political and macroeconomic instability, the strength of a country's institutions and governance frameworks, and the reliance on government revenues and GDP from mining. Initiatives like the EITI, the work of Multilateral Development Banks (e.g., the World Bank), and regulation in importing countries can play a role in influencing these factors (discussed in Section 4.7.2).

There are also several key actions that mining companies should prioritise:

Strong corporate governance: achieving sustainable and responsible materials supply should be a key priority of corporate strategy and across all business functions and decision-making.

Measurement and management of impacts: there are a number of steps that mining companies can take to improve how risks and impacts are addressed:

- Better identification and tracking of impacts, from annual carbon emissions and water use, to local land subsistence or respiratory diseases amongst workers.
- Proactively and openly discussing the trade-offs between different environmental and social objectives with local communities and policymakers, for example open pit mining has lower energy requirements but also results in more land change.
- Integrating environmental and social impact assessments within the early stages of project planning, monitoring, and community engagement. Issues must be identified and addressed before projects are approved.
- Develop continuous approaches to risk management, where procedures are improved on an ongoing basis in response to impacts and risks.

Community partnerships: investing in strong stakeholder relationships and building trust with local communities is a huge opportunity for mining companies, which in turn enables mining companies to build trust with investors and policymakers. Analysis of case studies, such as the Quellaveco mine in Peru [see Box I], suggests that features of successful partnerships include:

- A clear definition of the **common vision** and agreement on how to share local natural resources (e.g., how water from a reservoir will be allocated to mining versus farming).
- Local communities must be able to receive a **share in the benefits** generated from mining revenues, for example through investment by mining companies in community development, infrastructure, and skills and training.
- **Fair representation of the local community** in official engagement and, crucially, from the very initial stages of project planning.

Box I: Quellaveco, a 21st-century copper mine

Anglo American's $5.5 billion copper mine in Peru illustrates how a mine can be developed with sustainable economic development of the local area at its core.[257] To secure its environmental and social license to operate, Anglo American agreed to invest in the following:

- The development of a new water reservoir, built by Anglo American. Of the reservoir's 60 million m^3 of water, only 4 million m^3 are used by the mine, with the rest going to the local community and farmers. To supplement this water use, the mine will rely on water from a separate river which is naturally suffused with heavy metals and is therefore unsuitable for local human or agricultural use.

- The channelling of a local river to flow past the mine, to ensure its water is untouched.

- A $1 billion development fund over the 30 year life of the mine to pay for community projects.

- To hire and train local people and give opportunities to local suppliers. According to Anglo American, 70% of workers are from the local area and almost 30% are women (compared to 10% in other mines in Peru).

Critical to the success of this license was extensive dialogue and engagement between Anglo American, policymakers, local governors, and representatives from across the local community through 18 months of dialogue.

4.7.2 Recommendations for policymakers, regulators, and the private sector to enable and promote sustainable and responsible mining

To some extent, mining companies will invest in the actions and solutions discussed in the previous section to make their operations responsible and sustainable because there is a strong business imperative to do so. Three key drivers of this have been:

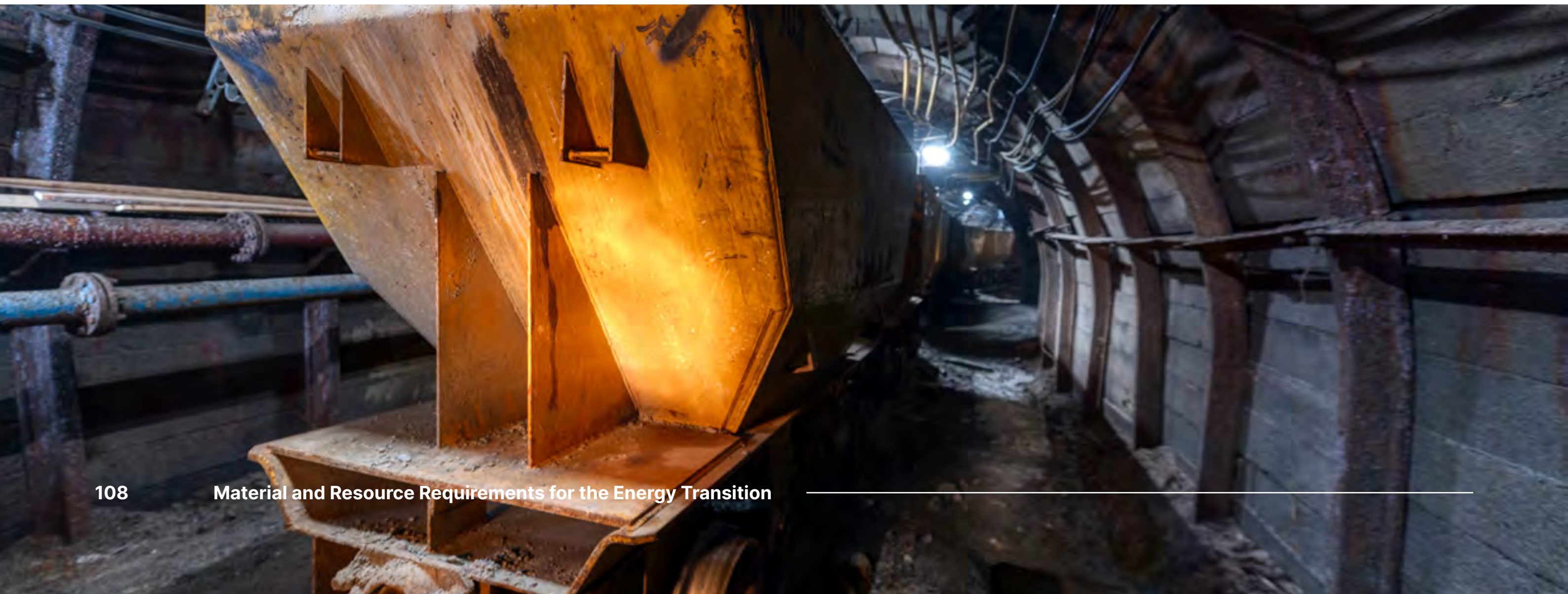
- Regulators, investors, manufacturers and consumers are increasingly demanding evidence of sustainable and responsible mining.

- Mining companies have made net-zero emissions and wider environmental commitments.

- The benefits outweigh the costs of such investments (e.g., protecting natural resources and community engagement increase business resilience and reduce downside risks).

However, because there typically is an upfront cost associated with such actions (both financial and a time cost), and because the returns may take time to materialise, business action alone is unlikely to be sufficient on its own to generate the system change needed across the sector globally.

257 Anglo American (2023), *Quellaveco mine;* Copper Alliance (2021), *Futuresmart Mining™ at Anglo American's Quellaveco mine: Smart, safe and sustainable;* The Economist (2022), *A test of whether big mining is socially sustainable.*



There are therefore a number of actions which policymakers and regulators, the downstream value chain, and financial institutions can take to mandate or incentivise such change:

Responsible actors: ● ◕ Leading actors ◑ ◔ Supporting actors

① Strengthen environmental regulations for mining and clean energy technology supply chains, starting with carbon intensity.

Policymakers & regulators	Downstream value chain	Financial institutions
●		

Regulation should start with strong requirements to reduce carbon emissions, for example by introducing carbon taxation for materials supply, or requirements for materials or clean energy technologies to have life-cycle emissions below a certain threshold – as is being discussed for upcoming EU regulation on batteries and will be implemented through the EU's Carbon Border Adjustment Mechanism.[258] A key part of this will be ensuring there are supporting real-economy policies incentivising, e.g., the deployment of clean energy technologies.

Over time and as a wider range of impacts are included in monitoring and transparency efforts, regulation should expand to cover additional impacts such as water intensity, local ecotoxicity, deforestation or biodiversity.

Regulations on environmental impacts can apply at both ends of the value chain:

- Regulations within mining countries, which directly regulate mining operations and determine the standards that a mine site must adhere to. In such cases, a priority must be to ensure that regulations have clear targets and standards, and that regulators are well-funded and have the capacity for strong enforcement.
  - For example, local governments could require mining companies to include indirect deforestation in environmental impact assessments, and in certain cases pay for monitoring and protection to ensure this does not take place.
- Regulations in countries or jurisdictions which import materials or final goods and which set criteria that must be met for importation/sale.

The more countries or jurisdictions which adopt strong regulations – and the more that these are broadly aligned and consistent across each other – the more effective regulation will be in influencing business decisions, as there is less opportunity for leakage to other less regulated markets.

As two of the world's largest consumer markets, regulations in the EU and the USA alone have the potential to act as a strong signal to mining companies and downstream manufacturers, and collaboration through bodies such as the G7, G20 and the OECD can help drive this even further.

② Use purchasing power to drive projects with high environmental and social standards

Policymakers & regulators	Downstream value chain	Financial institutions
●	●	

Governments should use their purchasing power to create a significant demand signal for products manufactured using sustainable and responsible materials. They can do this through clear public procurement standards for carbon emissions and environmental and social impacts. This could extend beyond clean energy technologies into other sectors (e.g., defence, construction).

A recent example is France's low-carbon regulation for solar modules.[259] Under the rules, any solar projects under public tenders must be below a threshold level level of carbon intensity. Similar proposals are part of the EU's Net Zero Industry Act, where sustainability and resilience requirements can make up 15–30% of awarding criteria for new clean energy technologies.[260]

258 EU Commission (2022), *Green Deal: EU agrees new law on more sustainable and circular batteries to support EU's energy transition and competitive industry;* EU Commission (2023), *Carbon Border Adjustment Mechanism.*
259 PV Magazine (2019), *The weekend read: Playing by the carbon footprint rules.*
260 These requirements would, however, be waived if they add over 10% to technology costs. BNEF (2023), *Europe's bid to reshore clean tech pulls its punches.*

Government purchasing power can also extend to buying critical raw materials, where governments establish strategic trade deals, advance purchase agreements, and so-called "buyer's clubs". There is an opportunity for governments to drive sustainable and responsible mining through these deals, tying purchases to clear environmental criteria and regulations – as is being proposed by the US Minerals Security Partnership, and in the EU's proposed Critical Raw Materials Club.[261]

In certain cases, outright procurement mandates or advance purchase agreements might be needed to specifically incentivise sustainable primary supply. This can help avoid leakage of impacts to other jurisdictions, or avoids stronger environmental and social standards simply being met by recycled supply.

Companies in the downstream value chain, namely manufacturers and retailers, can also send significant demand signals to the mining sector, for example through offtake agreements and by requiring companies to meet certain voluntary standards. For example, BHP have signed an agreement with Ford to supply low-carbon nickel for EV batteries,[262] and Apple have partnered with ELYSIS to make use of low-carbon aluminium in some iPhone production.[263]

③ Financial institutions can send a strong signal to the mining sector if investment decisions depend on sustainable and responsible production

Policymakers & regulators	Downstream value chain	Financial institutions
		●

While governments and manufacturers can send strong demand signals to the mining sector for sustainable and responsible production, financial institutions can exert significant pressure if investment is dependent on sustainable and responsible mining.

There are several reasons why financial institutions would prioritise financing for sustainable and responsible mining projects:

- **Expected returns could be higher**, for example due to greater demand from governments, manufacturers and ultimately end-consumers.
- **Downside risks are likely to be lower**, for example because of expectations of tighter regulation in key markets, or delays and additional costs due to opposition from local communities.
- **Net-zero or other ESG-related commitments**, which require financiers' portfolio of investments to be increasingly sustainable and responsible.

Given the dedicated expertise of voluntary standards organisations in auditing and appraising mining sites and companies, financial institutions – both private and multilateral development banks – should also increase efforts to leverage this expertise in informing their own assessments of mining projects and explore ways to tie investment decisions to sustainability and responsibility criteria. This is discussed in more detail in Section 4.7.3.

④ Drive adoption of supply chain traceability and commodity differentiation through industry-wide engagement and trusted third-party auditors

Policymakers & regulators	Downstream value chain	Financial institutions
◑	●	◑

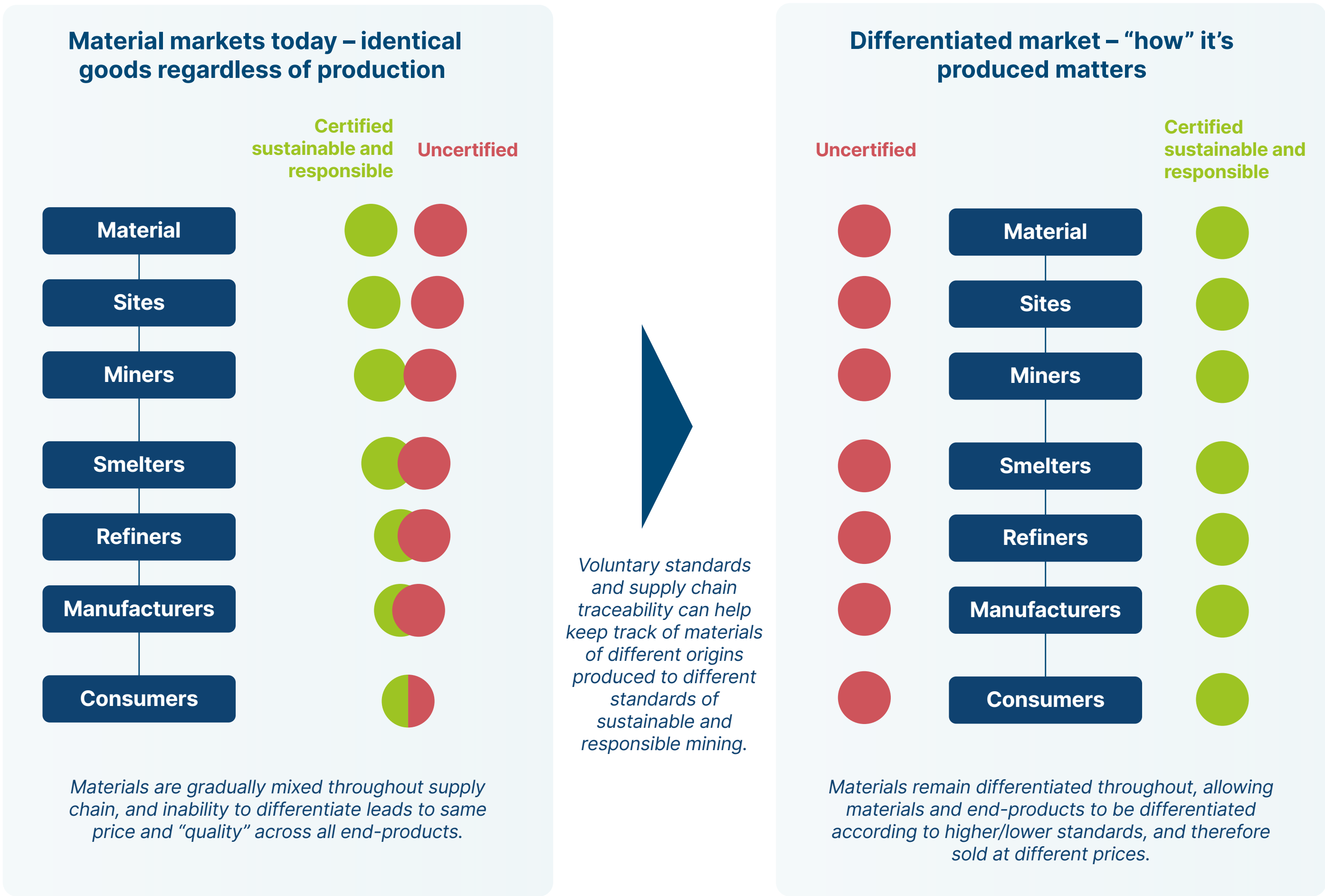
The current mining industry consists of a highly fragmented market with regard to environmental and social standards. The risk is that rapidly growing demand, in part driven by the energy transition, exacerbates such a situation. Supply chain traceability offers an opportunity to bring transparency to such impacts, and manage and reduce them.

Mining value chains are often complex, requiring lots of steps between materials being mined and being sold as part of a technology [Exhibit 4.9]. The blending and mixing that arises from these steps means it is hard to differentiate specific materials as they move down the value chain, with information on origins getting lost (unlike for consumable commodities, e.g., chocolate or coffee).[264]

261 US Department of State (2022), *Minerals Security Partnership;* EE News (2023), *EU to form €20bn critical materials club.*
262 BHP (2022), *BHP signs MOU for nickel supply with Ford Motor Company.*
263 ELYSIS (2022), *ELYSIS strengthens its ties with Apple.*
264 RMI (2022), *Supply Chain Traceability: Looking Beyond Greenhouse Gases.*

EXHIBIT 4.9

Supply chain traceability can enable materials to be differentially traded based on how they have been produced



SOURCE: Systemiq analysis for the ETC.

As mined materials are traded as undifferentiated, market demand signals for sustainable and responsible goods are lost. However, momentum is building from various players in mining supply chains for commodity differentiation:

- **Copper Mark**, a voluntary standards organisation, has developed a "Chain of Custody" standard, which aims to create transparency in how copper-containing products move through a supply chain.[265, 266]
- **START Responsible Aluminium** uses blockchain technology to collect data on and create a digital chain of every major event in a material's lifespan.[267] Rio Tinto and BMW Group have recently announced a partnership to deploy START and supply BMW's production plants with responsibly sourced aluminium.[268]
- **The EU's upcoming battery regulation** represents a step-change in the potential for supply chain traceability and transparency within the sector. This will include requirements for a "digital battery passport", enabling life-cycle tracing of a battery's carbon footprint, recycled content and supply chain due diligence obligations including environmental risks. This regulation is intended to create a level playing field for all batteries sold in the EU, regardless of the location of production, and will send a strong global demand signal for sustainable and responsible sourcing of key materials.[269]

265 Copper Mark (2023), *Chain of custody standard.*
266 Chain of custody refers to the flow of materials and goods from one end of the supply chain to the other. Various different models exist, including segregation models where the mixing of certified commodities is kept separate from noncertified products, and controlled blending models where a ratio of certified to noncertified products is specified. RMI (2022), *Supply Chain Traceability: Looking Beyond Greenhouse Gases.*
267 Start Responsible (2021), *Rio Tinto launches START.*
268 Rio Tinto (2023), *Road to a greener future: Rio Tinto partners with BMW Group on premium aluminium car parts.*
269 EU Commission (2022), *Batteries: deal on new EU rules for design, production and waste treatment;* Circulor (2022), *Breaking down the global relevance of the EU Battery Regulation.*

Actions to build upon this momentum for supply chain traceability and commodity differentiation include:

- **Policymakers and regulators** in countries outside the EU should develop similar regulation to the EU Battery Regulation, including requirements for "digital battery passports", which can amplify global demand signals for sustainable and responsible production. Regulation should start with easy-to-quantify metrics (e.g., carbon intensity, water use), and scale to encompass qualitative measures on, e.g., labour conditions, human rights.

- **Mining companies and manufacturers** should explore strategic partnerships to source sustainably and responsibly produced materials, deploying and developing approaches and technologies for tracing and auditing materials throughout supply chains.

  - As part of this, large-scale trials of traceability for sustainable materials and clean energy technologies should be carried out by 2030. For example, deploying a wind farm or producing an EV where most or all materials and impacts have been traced from mine to deployment.

- **Mining companies and voluntary standards organisations** should collaborate to develop and strengthen product-level standards, which are currently much weaker than site-level or company-level standards (see next section).[270]

Taking such actions would allow mining companies to be directly rewarded for sustainable and responsibly produced products in the form of higher prices.

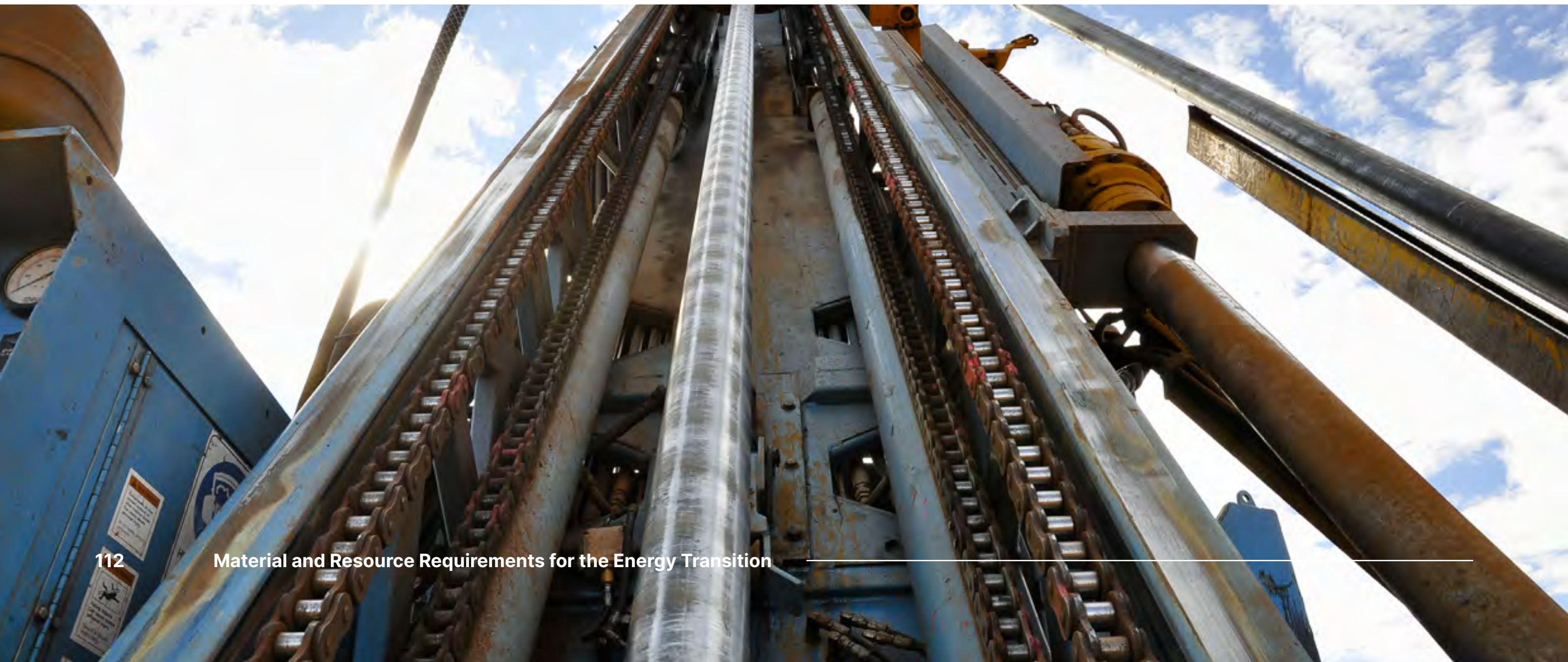
4.7.3 Making voluntary standards and certifications more effective in driving sustainable and responsible mining practices

Regulation sets out the mandatory requirements that mining or imported goods must adhere to within a certain jurisdiction, in effect setting a floor of minimum standards. Voluntary standards and certifications aim to go above this, by setting ambitious, globally-applicable criteria that mining sites and companies have to adhere to in order to be certified. In this way, they can incentivise companies to adopt best practices and converge towards sustainable and responsible mining, while also encouraging transparency and reporting of impacts across the sector. Certification provides mining companies with reputational benefits, enabling them to sell (potentially at a higher price) to more of the market.

There has been a proliferation of voluntary standards over the past decade. As outlined in Box J, these vary in terms of coverage (e.g., some are focused on just one material, while others cover a breadth of materials), the stringency and level of prescriptiveness of their criteria, and the audit process (e.g., boots-on-the-ground assessment, regularity of checks).

The growth of new voluntary standard organisations has largely been driven by downstream pressure from purchasers of materials, for example the automotive industry demanding to know more about the materials and resources they use. This pressure is, in turn, partly driven by increasing demands from consumers and regulators to know where and how materials have been produced. There is also growing interest in voluntary standards from investors (e.g., responsible pension funds), but this is relatively small-scale to date.

270 RMI (2022), *Supply Chain Traceability: Looking Beyond Greenhouse Gases.*



Box J: Voluntary standards

Voluntary mining standards typically cover a wide range of issues to promote sustainable and responsible mining. These include:[271]

- **Environmental responsibility:** how mining companies manage and limit their waste and tailings, water use, emissions, and pollution.
- **Social responsibility:** how mining companies ensure fair labour, promote health and safety, and contribute positively to local communities and economies, including leaving a positive legacy when a mining companies vacates a location.
- **Business responsibility:** how mining companies ensure legal and regulatory compliance, robust due diligence and risk management processes (e.g., human rights), engage with stakeholders (e.g., in the local community), and ensure revenue and payments transparency.

Standards can apply at various different levels:

- **Company-level:** an entire company's operations can be certified, covering many different mine sites and materials.
- **Site-level:** individual mining sites can be certified.
- **Product-level:** these standards can apply where mining sites can produce different quality outputs. These standards are less well developed within the critical raw materials sector, but are well established within gold, other metals, and fairtrade commodities. They can be a powerful tool for product differentiation if used widely.

EXHIBIT 4.10

Voluntary standards can apply to products, sites and companies, and can be material-specific or cover multiple materials

SOURCE: Systemiq analysis for the ETC.

NOTE: Listed voluntary standard organisations are examples; this list is not exhaustive. EITI = Extractives Industries Transparency Initiative; ICMM = International Council on Mining and Metals.

271 For example, see the Initiative for Responsible Mining Assurance (IRMA)'s (2018), *Standard for Responsible Mining.*

There are a number of challenges which currently limit the effectiveness of the voluntary standards market:

- **There are too many standards:** The proliferation of different standards dilutes the market signals that certification can provide to purchasers, financial institutions and consumers, while also reducing confidence in any one standard. In addition, it increases the burden on companies to navigate which standards to adopt and to understand how different standards map against each other.

- **Many standards lack robustness:** In some cases, there are issues with the standards themselves, including a lack of ambition and clarity in terms of requirements, and in certain cases standards can lack decision-making influence within industry. In addition, there are often long time lags between audits and insufficient funding for sufficient "boots on the ground".

- **Standards don't speak to investors and consumers:** Data, evidence and results are not communicated in a meaningful way to purchasers or consumers, due to difficulties in cross-comparing different standards with different formats, or mapping them onto regulations. In addition, there is uncertainty around which standards are "best" or most relevant to an investor's or consumer's concerns, making it challenging to understand how performance on different criteria might impact decision-making.

- **Standards don't reach the bottom of the market:** Typically, only top-performing or publicly-exposed companies adopt voluntary standards, leaving a large part of the market behind and subject only to country-specific regulations which can vary widely in strength and enforcement. There is therefore a limit to what voluntary standards can achieve in countries with poor governance, human rights or regulatory frameworks.

There is strong potential to improve the voluntary standards system through consolidation, alignment and better signalling. Several actions could help to achieve this:

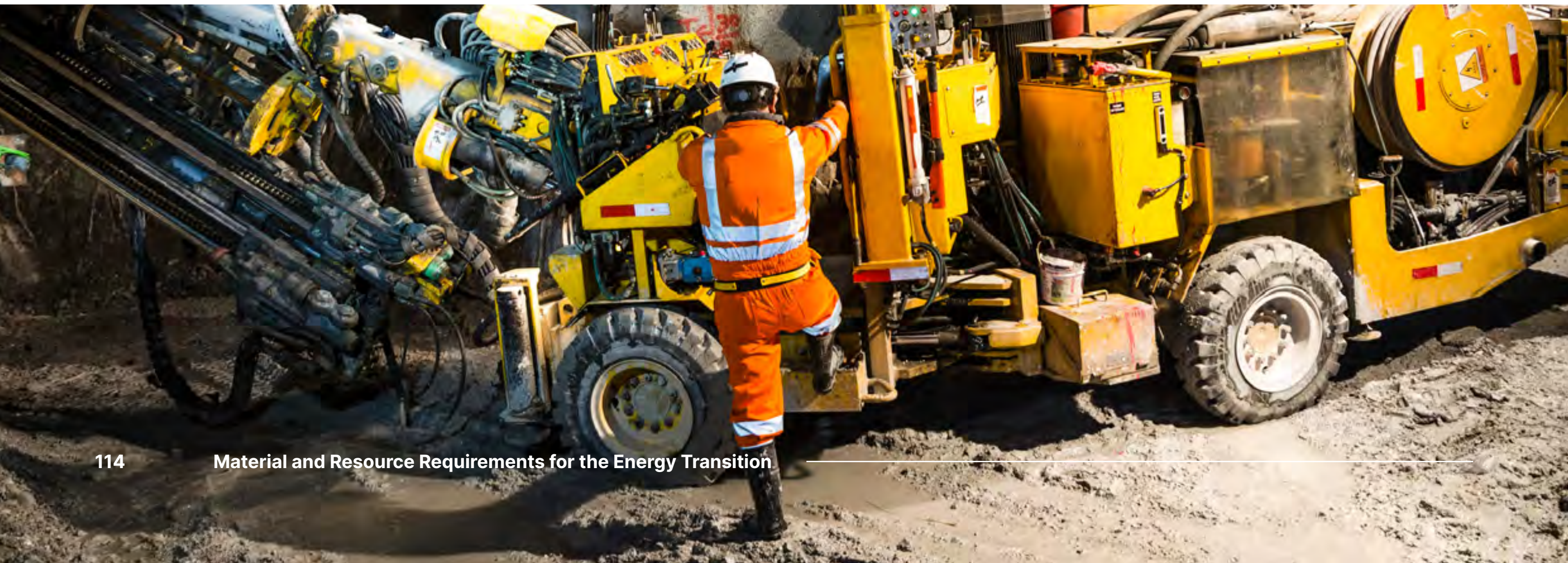
- International organisations or forums (e.g., the OECD, or through the UNFCCC's Climate Change Conferences) should **facilitate a dialogue** between voluntary standards organisations, mining companies, buyers to identify the opportunities for upwards **harmonisation of global standards**.
    - This should build upon comprehensive mapping of how different voluntary standards compare and relate to each other – as has already been done, to a degree, by organisations such as Securing America's Future Energy and the German Federal Institute for Geosciences and Natural Resources, and in the equivalence principles developed by ICMM.[272]

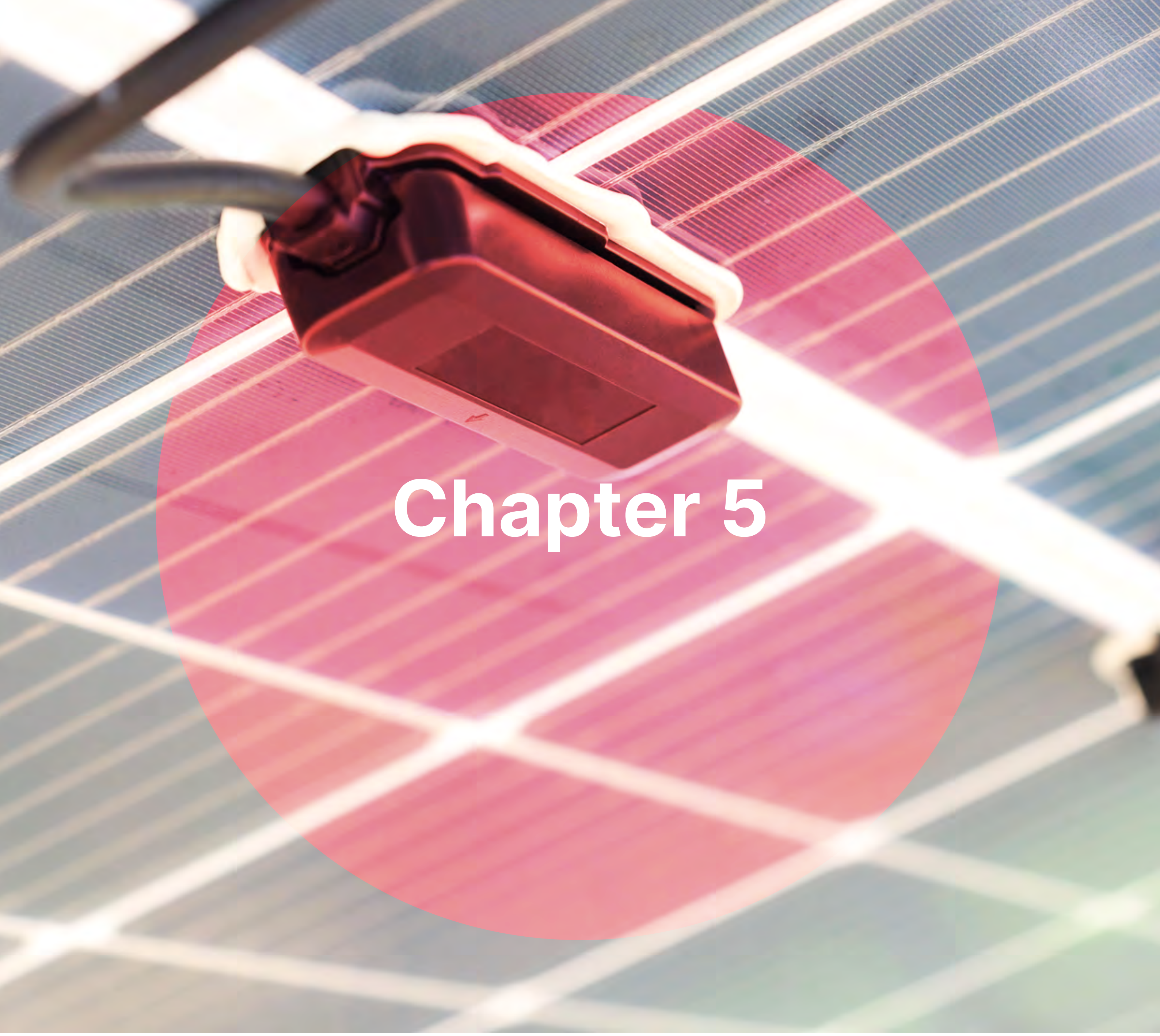
- National governments and MDBs can **set out clear principles or baselines that all standards must meet**. This would send a strong signal to the mining and downstream sectors to focus on the set of voluntary standards that meet this level, and could drive consolidation.

- **Financial institutions and voluntary standards organisations should proactively engage** with each other to identify ways that standards and the results of assessments can more usefully inform investor decision-making. Alternatively, or additionally, industry bodies (such as the Institutional Investors Group on Climate Change)[273] can develop their own frameworks and criteria to incorporate sustainable and responsible mining considerations into investment decisions.

272 Securing America's Future Energy (2023), *A global race to the top for critical minerals;* BGR (2022), *Sustainability standard systems for mineral resources;* ICMM (2020), *ICMM announces equivalency benchmarks with other responsible sourcing standards.*

273 The IIGCC is a European membership body which works with business, policy makers and fellow investors to help define the investment practices, policies and corporate behaviours required to address climate change.





Implications for clean energy technologies and key actions for the 2020s

Batteries and electric vehicles face the greatest challenges to scaling supply of critical materials quickly and sustainably. Supply blockages could lead to high prices, potentially slowing price declines for batteries, delaying EV adoption and the decarbonisation of road transport. To avoid these risks action must be taken on four fronts: reducing the pressure on primary supply, increasing mined supply, making future supply resilient and secure, and ensuring sustainable and responsible production.

This report has set out three key challenges facing material requirements for the energy transition: supply struggling to keep pace with rapidly growing demand, concerns around geopolitics and concentration of supply, and the environmental and social impacts of scaling supply.

Given the need for rapid ongoing deployment of clean energy technologies, strong actions from industry and policymakers will be needed to address these challenges and ensure as smooth a scale-up as possible.

This chapter provides a summary of cross-cutting risks for clean energy technologies, outlines potential implications for batteries and electric vehicles, and sets out priority actions for the remainder of this decade.

5.1 Summary of key risks and potential short-term implications

A cross-cutting assessment of the risks for rapid deployment of clean energy technologies, including the challenges outlined above, leads to the conclusion that risks from materials supply are highest for batteries and electric vehicles [Exhibit 5.1]:

- **Batteries and EVs are the technology most at risk** due to the potential for supply bottlenecks and gaps in 2030 for lithium, nickel, graphite, cobalt, neodymium and copper. These risks are amplified by risks of the strong concentration of supply chains and various environmental and social risks, ranging from the mining of cobalt in the DRC, to water-intensive lithium production or emissions-intensive nickel supply.
- **Solar PV** does not face any major material constraints; however, the production of polysilicon for solar panels faces challenges due to the high concentration in China and associated social and environmental risks. More significant challenges to solar deployment, however, are more likely to appear around planning and permitting requirements and grid connection queues.[274]
- The build-out of **transmission and distribution grids** could face challenges from high copper prices – although there is some potential for thrifting and substitution, as outlined in Chapter 2. Challenges to grid scale-up are more likely to manifest in terms of grid build-out timescales.[275]
- Other clean energy technologies may face more minor, specific challenges to material supply but these are unlikely to significantly delay deployment.

274 ETC (2023), *Streamlining planning and permitting to accelerate wind and solar deployment.*

275 This topic will be covered in detail in an upcoming ETC report. See e.g., Financial Times (2023), *Grid bottlenecks delay transition to clean energy.*

EXHIBIT 5.1

Implications of critical minerals supply challenges for clean energy technologies

	Key Materials	Materials Availability	Risk	Supply concentration, environmental and social impacts	Risk
Batteries and Electric Vehicles	Lithium Nickel Cobalt Graphite Copper Neodymium	• Batteries and EVs face strongest potential supply bottlenecks for raw materials. • Potential supply gaps in 2030 for lithium, nickel, cobalt, graphite, neodymium and copper. • Also downstream supply gaps for refined products (e.g. nickel sulphate, lithium carbonate/hydroxide).	3 Mid/High	• Strong concentration of supply chains, especially for refining of key battery materials in China. • Cobalt production in DRC associated with poor working conditions and child labour, and high biodiversity impacts. • Lithium production is highly water and carbon intensive. • Future nickel production from laterites in Indonesia is very emissions intensive – high use of coal power in grid.	4 High
Solar	Polysilicon Silver Copper Aluminium	• Polysilicon supply responds to price and demand very rapidly, and is not constrained. • Silver use is significant but expected to fall as technology and material efficiency develop. • Supply of copper for wiring and local grid connection may be expensive or somewhat constrained.	2 Low/Mid	• Polysilicon supply and downstream solar PV supply chain highly concentrated in China. • Human rights concerns for polysilicon supply in Xinjiang. • Polysilicon production is currently highly energy- and emissions-intensive and needs decarbonising rapidly.	4 High
Power Grids	Copper Aluminium	• Grid expansion will drive very large rise in demand for copper and aluminium. • For copper, there are likely to be high prices and/or supply constraints. • Swapping copper with aluminium, increased use of HVDC, thrifting etc. is possible in some cases but will not solve copper constraints entirely.	3 Mid/High	• Aluminium production is highly distributed, copper fairly distributed, both markets highly commoditised. • Copper production faces falling ore grades, driving up energy and water intensity and generating large volumes of waste rock/tailings.	2 Low/Mid
Wind	Steel Neodymium Copper Concrete	• Over 90% of total material requirements for wind turbines are steel and concrete, for which there are no availability concerns. • Scale-up in supply of rare earth elements might be a concern, but can shift to less REE-intensive models. • Supply of copper for wiring and local grid connection may be expensive or somewhat constrained.	2 Low/Mid	• Mining and refining of REEs is heavily concentrated in China. • REE mining produces significant toxic waste and pollution at local scale. • Production of steel and concrete is currently emissions-intensive and needs decarbonising rapidly.	2 Low/Mid
Electrolysers and Fuel Cells	Platinum Palladium Nickel	• Rapid innovation is reducing requirements for PGMs. • Demand for PGMs in any case will be well below volumes currently used in auto catalysts. • Nickel requirements are significant but far smaller than demand from BEVs.	2 Low/Mid	• Mining of PGMs is strongly concentrated in South Africa, with Russia also producing large proportion of Palladium. • Due to very low ore grades for PGMs, mining is strongly water, energy- and emissions-intensive and produces large amounts of tailings and waste rock per ton.	2 Low/Mid
CCUS	Steel Concrete Chemical Sorbents	• CCUS/DAC requires low amounts of structural steel, concrete etc. • CCUS relies on chemicals (e.g., monoethanolamine) as sorbents to remove carbon dioxide. Large ramp-up in supply required, but this should is within historical precedent of industry.	2 Low/Mid	• Production of chemical sorbents for CCUS currently relies on petrochemicals/fossil fuel industry – but potential to switch to synthetic feedstocks in coming decades, or swap to other sorbent-free approaches.	2 Low/Mid
Nuclear	Steel Concrete Uranium	• Nuclear power has lower steel, concrete, copper requirements per GW of capacity than wind and solar, and supply is not a concern. • Uranium fuel supply would need to expand to meet demand, but newer reactors have lower fuel requirements. • Recycling of spent uranium fuel rods can be done and is likely to increase.	1 Low	• Uranium mining is fairly geographically concentrated, (Kazakhstan ~40%, Australia, Namibia and Canada ~10%). • Uranium mining leads to radioactive contamination of waste and production of radioactive dust – but volumes are very low. • Spent uranium fuel needs careful storage over very long-term.	2 Low/Mid

The implications of such risks for electric vehicles could be significant. BNEF estimate that average lithium-ion battery pack prices rose 7% between 2021–22, slowing long-term cost declines (known as "learning rates") from around 18% each year to 17% each year, predominantly due to the exceptionally high battery-material prices seen throughout that period [Exhibit 5.2].[276]

If high battery material prices persist through to 2030, slowing learning rates to 16% per annum, we estimate that this could lead to prices being around 45% higher than if they continued decreasing by 18% each year. Small but sustained increase in prices can have a large cumulative impact on the price of clean energy technologies, delaying deployment. For example, given batteries make up 20–30% of upfront vehicle costs, this could delay electric vehicle "cost-parity" by two to three years across the US, Europe and China [Exhibit 5.2].

The long-term consequences of such a delay would be significant: hundreds of millions of internal combustion engine vehicles remaining on the road for many more years, leading to around 6 $GtCO_2$ of additional emissions between now and 2050.

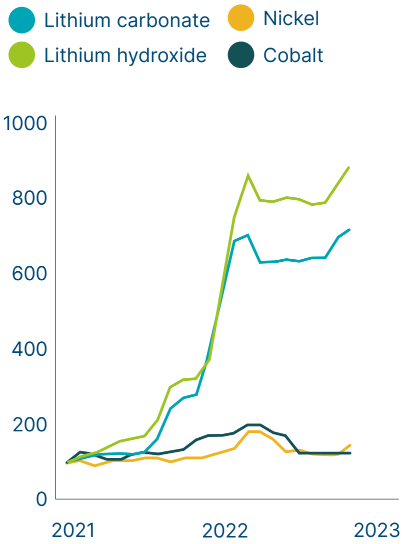
Although this example focuses on batteries and EVs, if significant and sustained market tightness and lack of supply is seen for copper, a similar pattern could be seen in the increased cost and slower deployment of solar, wind and power grids – delaying the transition and leading to higher future emissions.

276 BNEF (2022), Lithium-ion battery price survey.

EXHIBIT 5.2

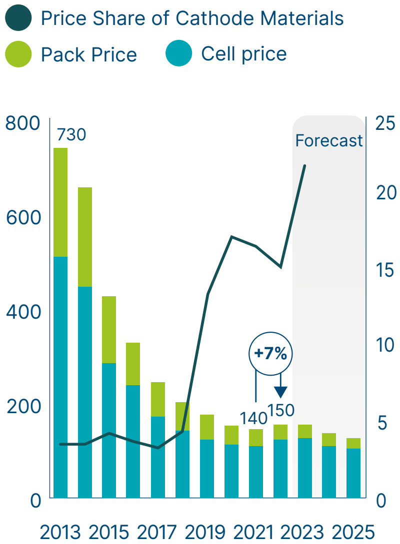
High material prices can slow cost declines for batteries, delaying EV uptake and leading to higher emissions from passenger vehicles

Cathode material prices
Jan 31st 2021 = 100



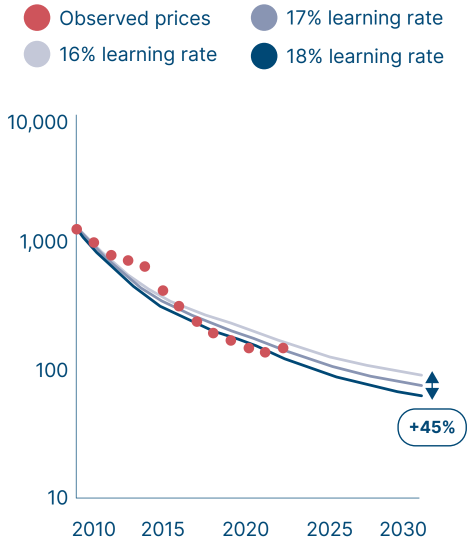
Key battery material prices spiked sharply throughout 2021–22.

Li-ion battery price
2022 US$/kWh



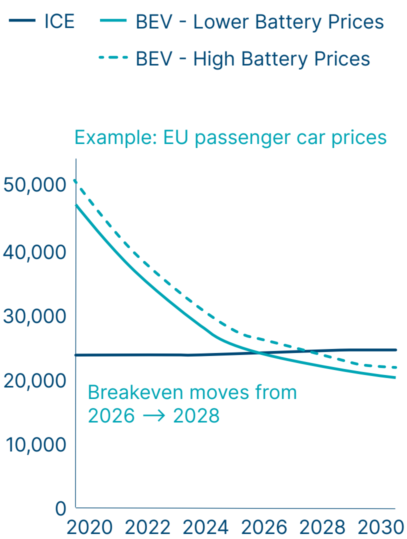
Spike in cathode material prices led to a 7% increase in average battery prices in 2022.

Li-ion battery cost curves[1]
2022 $/kWh

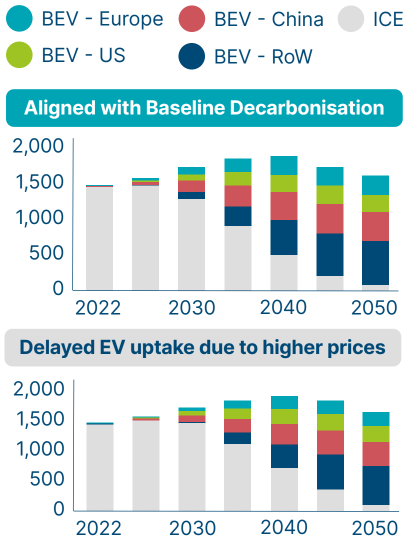


If material prices remain high, this could limit the pace of price declines in coming years.

Upfront passenger car prices
$



Global passenger vehicle fleet
Millions of vehicles



Around **200m additional ICE vehicles on the road** between 2030–35 due to slow BEV uptake

Ongoing use of ICE vehicles could mean **additional emissions of ~6 $GtCO_2$ between 2020–50[2]**

[1] A "learning rate" is the pace at which technologies experience cost declines as manufacturing and capacity increases over time – these are typically plotted on so-called "cost curves". Learning rates for lithium-ion batteries have seen 16–17% per annum cost declines over the past decade.

[2] Assumes average annual distance travel of ~15,000 km per vehicle at an emissions intensity of 100 gCO_2/km.

SOURCE: Systemiq analysis for the ETC based on Transport & Environment (2021), *Hitting the EV inflection point*; International Council on Clean Transportation (2019), *Update on electric vehicle costs in the United States through to 2030*; International Council on Clean Transportation (2021), *Evaluating electric vehicle costs and benefits in China in the 2020-2035 time frame*; BNEF (2022) *Long-term electric vehicle outlook*; BNEF (2022), *Lithium-ion battery price survey.*

Whilst these risks are significant over the short-to-mid-term, they do not pose a fundamental obstacle for the energy transition for three key reasons:

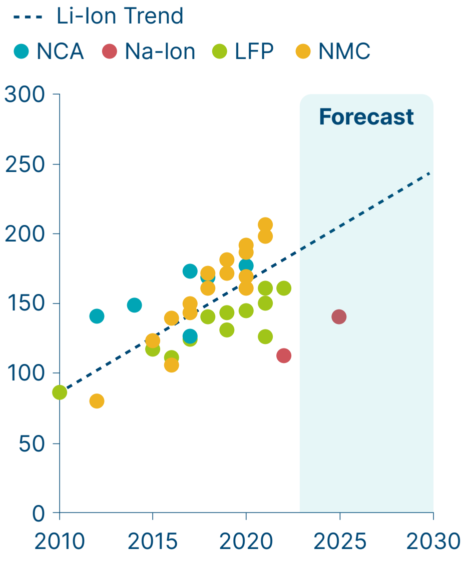
- Whatever the short-term price trends, the long-term drivers for cost declines (i.e. learning curves, economies of scale) for clean energy technologies remain in place and are expected to continue.
- As this report has outlined, there are many actions that policymakers, the private sector, and financial institutions can take to alleviate pressure on mining supply, reduce price volatility and scale supply quickly and sustainably.
- Mining and material markets have always been characterised by volatile prices; and it’s high/volatile prices which can actually act as an incentive to invest and innovate.

As outlined in Chapter 2, continuous innovation in technology performance, new technology options, and reduction or substitution in materials intensity can significantly reduce total demand for energy transition metals. This helps not only reduce supply-demand imbalances, but also drives down risks associated with concentration of supply and the environmental and social impacts of materials supply. Thus, driving further innovation across clean technologies e.g., battery energy density, wind turbine capacity, or solar PV module efficiencies will be crucial in coming decades [Exhibit 5.3].

EXHIBIT 5.3

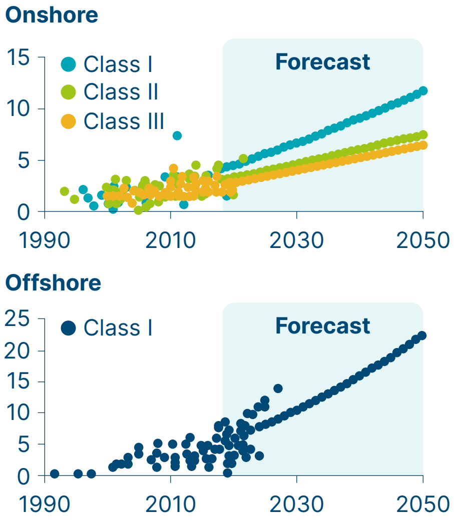
Innovation in clean energy technologies needs to keep progressing in coming years

Li-ion battery pack energy density[1]
Wh/kg



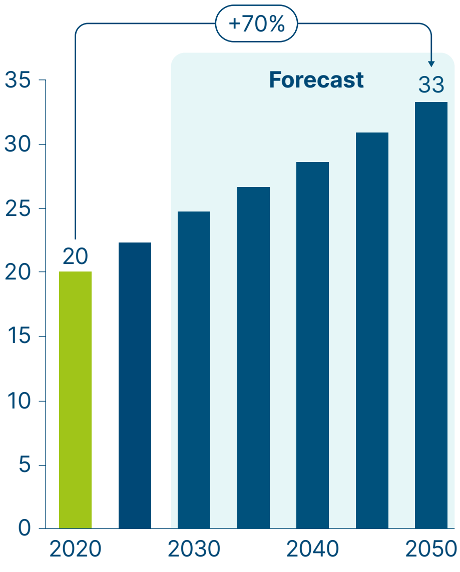
New chemistries and innovative cells and packs help drive higher battery energy densities.

Historical and forecast wind turbine capacity
MW



Larger wind turbines help reduce materials intensity for every MWh of clean electricity generated.

PV module efficiency forecast
Power conversion efficiency, %



Solar efficiencies will keep rising steadily, reducing materials and land needed for every GW installed.

[1] Gravimetric energy density, defined as available stored energy per unit mass.

NOTE: Class I/II/III refers to the wind speed that turbines are designed to operate in. Class I turbines are designed for higher windspeeds, and would have smaller blades, shorter towers and more robust designs.

SOURCE: BNEF (2022), *Long-term electric vehicle outlook*; BNEF (2020), *35MW Wind turbines to lower material demand*; BNEF (2023), *Transition metals outlook.*

5.2 Key actions for the 2020s

None of the risks and challenges outlined in this report are insurmountable. Actions by policymakers and regulators, combined with strong private sector leadership to innovate and promote sustainable and responsible mining, can reduce the risks of a delayed or more expensive transition. Addressing challenges to materials supply requires action on four fronts:

- **Alleviating pressure on primary supply**, by accelerating technology and materials efficiency and scaling recycling across clean energy technologies and materials. This was covered in Chapter 2.
- **Expanding mined supply by** creating clarity on future demand, reducing mine development timescales, increasing financing for mining, boosting mine production, and improving international collaboration and data-sharing. This was covered in the first half of Chapter 3.
- **Diversifying and securing sources of supply** over the short-to-mid-term, to reduce risks from concentration of supply, and carefully weighing up the costs and potential benefits of near-shoring of supply. This was covered in the second half of Chapter 3.
- **Mitigating environmental and social impacts** through strong regulation, backed by widespread use of voluntary standards and supply chain traceability – driven by best-in-class actors in the mining sector. Actions for mining companies, and for policymakers and financial institutions, were outlined in Chapter 4, and five areas of priority were highlighted above.

To bring focus to such actions, key targets for industry and policymakers by 2030 could include:

Scaling Primary Supply	More Recycling	Driving Efficiency	Increased Investment
Scaling primary supply of materials to: >550 kt p.a. of lithium (120 kt in 2022) >30 Mt p.a. of copper (22 Mt in 2022) >4 Mt p.a. of nickel (3.3 Mt in 2022) >6 Mt p.a. of natural and synthetic graphite (1 Mt in 2022) >250 kt p.a. of cobalt (150 kt in 2022)	**Scaling secondary supply** of materials to: >5 Mt p.a. of secondary supply of copper (3 Mt in 2022) Recycling capacity for >1 Mt of battery materials. (0.1 Mt in 2022) **End-of-life recycling rates of over 70%** for copper and battery materials.	**Materials and Technology Shifts:** Rapid shift to LFP batteries to over 40% of market, and fast growth of Na-ion to >5% market share. Higher substitution of copper in grids, reduced use of REEs in wind turbines and EVs. **Technology performance:** Battery pack energy densities >250 Wh/kg (vs. 180 Wh/kg in 2022) Solar PV efficiencies reach >24% conversion efficiency (vs. 20% in 2022). Electrolyser efficiencies below 50 kWh/kg H2 (vs. 53 kWh/kg H2 in 2022). On/Offshore wind capacity factors above 30/45% (vs. 25/40% in 2022).	**$70bn p.a. in mining** of copper, lithium, nickel, cobalt and graphite (vs. $45bn in 2022). **$70-100bn p.a. in refining** of copper, lithium, nickel, cobalt and graphite. **$3-4bn p.a. in recycling** of copper and batteries.

Energy Transitions Commission

MATERIALS AND RESOURCES

2030 TARGETS

ACTIONS REQUIRED FOR A SUSTAINABLE AND RESPONSIBLE MATERIAL SCALE-UP

PRIMARY SUPPLY

- **550 kt** — Annual lithium production (from 125 kt)
- **30 Mt** — Annual copper production (from 22 Mt)

RECYCLED SUPPLY

- **>1 Mt** — Battery materials (from 0.1 Mt)
- **>5 Mt** — Secondary copper (from 4 Mt)

EFFICIENCY

- **250 Wh/kg** — Battery pack energy density (from 160 Wh/kg)
- **24%** — Solar panel efficiency (from 20%)
- **30/45 %** — On/Offshore wind capacity factors (from 25/40%)

INVESTMENT

- **$70 bn p.a.** — Mining for copper, lithium, nickel, cobalt, graphite (from $45bn)
- **$70-100 bn p.a.** — Refining for copper, lithium, nickel, cobalt, graphite
- **$3-4 bn p.a.** — Recycling for copper and batteries

Four priority actions

Fundamental driver: **a strategic vision for the energy transition**, supported by well-designed policies which send clear signals on the pace and scale of the transition and remove barriers to deploying clean energy technologies.

KEY ACTORS: LEADING ACTORS / SUPPORTING ACTORS

Priority action	Action	POLICY-MAKERS/ REGULATORS	MINING COMPANIES	DOWNSTREAM VALUE CHAIN	OTHER ACTORS
1 REDUCE PRESSURE ON PRIMARY SUPPLY	*Demand*: Accelerate improvements in **materials and technology efficiency**, e.g. through increased R&D, public 'moonshot' targets, and more circular design.	Supporting		Leading	
	Supply: **Scaling recycling**, re-use and secondary supply, driven by regulation and economic incentives.	Leading	Supporting	Supporting	RECYCLERS (Leading)
2 EXPAND MINED SUPPLY	**Expand supply from the mine site** by: reducing mine development timescales, increasing investment, raising mine output, and improving international collaboration and data-sharing.	Supporting	Leading		INVESTORS (Leading)
3 BUILD RESILIENT AND SECURE SUPPLY	**Adopt strategies to diversify and secure supply** over the short-to-mid term to reduce risks from concentrated supply.	Leading	Supporting	Leading	
	Where near-shoring is strategically beneficial, ensure benefits are maximised by e.g., aligning with domestic growth sectors.	Leading		Supporting	
4 DRIVE SUSTAINABLE AND RESPONSIBLE SUPPLY CHAINS	Strong **regulations on carbon intensity** of materials production.	Leading			
	Reduce local environmental impacts of materials supply and engage with local communities to **secure trust and consent**.		Leading	Leading	CIVIL SOCIETY (Supporting)
	Use purchasing power to drive projects with high environmental and social standards.	Leading		Supporting	INVESTORS, DEVELOPMENT FINANCE (Supporting)
	Define and adopt **high-quality voluntary standards**, and improve and require **supply chain traceability**.	Leading	Supporting		VOLUNTARY-STANDARDS ORGANISAITONS (Leading)

Energy Transitions Commission - July 2023

Appendix

Overview of key model assumptions, grouped by technology (not exhaustive)

Technology	Baseline Decarbonisation Key Assumptions	High Efficiency Key Assumptions	High Recycling Key Assumptions
Solar	**Lifetime** 30 years **Capacity Factor (Global Avg.)** 14% rising to 15.5% by 2050. **Market Shares** 95% silicon-based through to 2050. **Materials Intensity** • Aluminium: 15 t/MW, falling to 12 t/MW by 2050. • Copper: 3.2 t/MW, falling to 2.6 t/MW by 2050. • Silicon: 3 t/MW, falling to 2 t/MW by 2050. • Silver: 17 kg/MW, falling to 11 kg/MW by 2050.	• Capacity factors rise to 17% by 2050 (vs. 15.5%). • Silicon intensity falls to 2/1 kg/MW in 2040/50 (vs. 2.5/2). • Silver intensity falls to 13/9 kg/MW (vs. 14/11).	• 70/90% of solar panels collected at end of life in 2040/50. • Silicon end of life recycling rate reaches 90% by 2040. • Silver end of life recycling rate reaches 80/90% by 2040/50.
Wind	**Lifetime** 30 years **Capacity Factor (Global Avg.)** • Onshore: 25% rising to 37% by 2050. • Offshore: 40% rising to 50% by 2050. **Market Shares** • 90% Onshore, shifting to 60% by 2050. • Onshore: 72:5:18:5 split across GB-DFIG/GB-PMSG/DD-PMSG/DD-EESG, shifting to 65:15:15:5 by 2050.[277] • Offshore: 5:20:75:0 split across GB-DFIG/GB-PMSG/DD-PMSG/DD-EESG, shifting to 0:10:90:0 by 2050. **Materials Intensity** *GB-Based:* • Concrete: 500 t/MW, falling to 400 t/MW by 2050. • Steel: 140 t/MW, falling to 110 t/MW by 2050. • Neodymium: 12/50 kg/MW, falling to 7/28 kg/MW by 2050. *DD-Based:* • Concrete: 800 t/MW, falling to 625 t/MW by 2050. • Steel: 400 t/MW, falling to 320 t/MW by 2050. • Neodymium: 180/28 kg/MW, falling to 100/15 kg/MW by 2050.	• On/Offshore capacity factors rise to 41/55% by 2050 (vs. 37/50%). • Onshore:Offshore split reaches 50:50 by 2050 (vs. 60:40). • Higher share of market for low-REE turbine designs (away from GB-PMSG). • Steel and copper intensity per MW falls by 15/30% by 2040/50.	• 70/90% of wind turbines collected at end of life in 2040/50. • Steel reaches 90% end-of-life recycling rate by 2040.

277 GB = Gearbox, DD = Direct-Drive, DFIG = Double-Fed Induction Generator, PMSG = Permanent-Magnet Synchronous Generator, EESG = Electrically-Excited Synchronous Generator.

Nuclear Power	**Lifetime** 50 Years **Capacity Factor** 80% **Materials Intensity** • Concrete: 640 t/MW, falling to 510 t/MW by 2050. • Copper: 1.5 t/MW, falling to 1.2 t/MW by 2050. • Steel: 90 t/MW, falling to 72 t/MW by 2050. • Uranium: 24 t/TWh, falling to 17 t/TWh by 2050.	• Nuclear capacity factors reach 88% by 2040 (vs. 80%). • Lower and falling nuclear fuel requirements of 16/13 kg/GWh in 2040/50 (vs. 19/17).	• Uranium reaches end-of-life recycling rate of 80/90% by 2040/50 (vs. 50%).
Transmission and Distribution Grid	**Lifetime** 60 Years **Capacity Factor** • Transmission: 4150 TWh/million km, rising to 4300 TWh/million km by 2050. • Distribution: 430 TWh/million km, falling to 410 TWh/million km by 2050. **Market Shares** • Transmission: 75:20:5 Overhead/Underground/Submarine, shifting to 65:28:7 by 2050. • Distribution: 75:25 Overhead/Underground, shifting to 65:35 by 2050. **Materials Intensity** *Transmission – Overhead* • Aluminium: 5 t/km, falling to 4 t/km by 2050. *Transmission – Underground* • Aluminium: 5 t/km, falling to 4 t/km by 2050. • Copper: 8 t/km, falling to 6.5 t/km by 2050. *Transmission – Submarine* • Aluminium: 1 t/km, falling to 0.8 t/km by 2050. • Copper: 8 t/km, falling to 6.5 t/km by 2050. *Distribution – Overhead* • Aluminium: 2 t/km, falling to 1.5 t/km by 2050. *Distribution – Underground* • Aluminium: 1.5 t/km, falling to 1.2 t/km by 2050. • Copper: 2.5 t/km, falling to 2 t/km by 2050.	• More efficient grid build-out and management leads to smaller grid: 13.5/16.5 million km in 2040/50 for transmission (vs. 15/18), 135/170 million km for distribution (vs. 150/190). • Higher share of overground cables, which are less materials-intensive. • Increased substitution of copper for aluminium in underground cables.	• 80/90% of grid equipment collected for recycling at end of life in 2040/50. • Copper end-of-life recycling rate reaches 90% by 2030. • Aluminium end-of-life recycling rate reaches 90% by 2040.

Electric Vehicles	**Lifetime** Passenger: 15 years Commercial: 18 years **Battery Size (Global Avg.)** • *Passenger:* 55 kWh, rising to 70 kWh by 2050. • *Commercial – Light-Duty:* 45 kWh, rising to 70 kWh by 2050. • *Commercial – Heavy-Duty:* 250 kWh, rising to 450 kWh by 2050. **Battery Market Shares** • *Passenger:* 30:50:20 split LFP/NMC/Other, shifting to 30:10:60 by 2050.[278] • *Commercial:* 30:35:35 split LFP/NMC/Other, shifting to 20:15:65 by 2050.[279] **Battery Materials Intensity** Variable by battery chemistry, across lithium, cobalt, nickel, graphite.[280] **Vehicle Materials Intensity** *Passenger:* • Copper: 60 kg/vehicle, falling to 48 kg/vehicle by 2050. • Neodymium: 0.36 kg/vehicle, falling to 0.29 kg/vehicle by 2050. *Commercial – Light-Duty:* • Copper: 120 kg/vehicle, falling to 95 kg/vehicle by 2050. • Neodymium: 0.72 kg/vehicle, falling to 0.58 kg/vehicle by 2050. *Commercial – Heavy-Duty:* • Copper: 300 kg/vehicle, falling to 240 kg/vehicle by 2050. • Neodymium: 1.8 kg/vehicle, falling to 1.4 kg/vehicle by 2050.	• Smaller batteries: total fleet requires battery capacity of 30/95/130 TWh (vs. 30/110/160). • Higher market shares for new chemistries (especially LFP and Na-ion). • Faster and greater reductions in materials intensity. • Less degradation of batteries for re-use in stationary storage at end-of-life.	• 80/90% of batteries collected for re-use or recycling at end of life in 2040/50. • Recycling rates for cobalt, nickel and graphite reach 90% by 2040 (85% for lithium).
Stationary Storage	**Lifetime** 12 years **Market Shares** 50:30:15:5 split LFP/NMC/NCA/Other, shifting to 20:10:70 split LFP/Vanadium/Na-Ion by 2050. **Materials Intensity** Variable by battery chemistry, across lithium, cobalt, nickel, graphite.[281]	• Higher market share earlier on for vanadium redox-flow and Na-ion batteries. • Faster and greater reductions in materials intensity.	• 25/30% of EV batteries re-used for stationary storage, providing up to 0.5/1.5 TWh by 2040/50.

278 LFP includes LFP and LMFP; NMC includes NMC-622 and NMC-811; Other includes LMR-NMC, LNO, LNMO, NCA, Na-Ion, NCA. Based on BNEF (2022), Long-term electric vehicle outlook.
279 Ibid.
280 Based on BNEF (2022), *Long-term electric vehicle outlook;* Argonne National Laboratory (2022), *BatPaC software.*
281 Ibid.

Hydrogen Electrolysers	**Lifetime** 20 Years **Load Factor** 60% falling to 45% by 2050. **Efficiency** 53 kWh/kgH_2, falling to 48 kWh/kgH_2 by 2050. **Market Shares** 80:20 constant split Alkaline:PEM. **Materials Intensity** *PEM* • Platinum: 0.3 kg/MW, falling to 0.1 kg/MW by 2050. • Palladium: 2.5 kg/MW, falling to 1 kg/MW by 2050. *Alkaline* • Nickel: 3.2 t/MW, falling to 2.6 t/MW by 2050.	• Electrolyser efficiency reaches 43 kWh/kgH_2 by 2050 (vs. 48). • Electrolyser load factors decrease more slowly, reaching 53/50% by 2040/50 (vs. 50/45). • Higher market share for SOEC electrolysers: 5/12.5/15% in 2030/40/50 (vs. no share). • Faster and greater reductions in materials intensity of nickel, platinum, palladium.	• 70/90% of electrolysers collected for recycling at end of life by 2040/50. • Platinum and palladium end-of-life recycling rate reaches 75/90% by 2040/50.
Hydrogen Fuel Cells	**Lifetime** 15 Years **Efficiency** 40% rising to 55% by 2050. **Market Shares** 100% PEM, shifting to 90:10 PEM/Alkaline by 2050. **Materials Intensity** *PEM* • Platinum: 0.3 kg/MW, falling to 0.1 kg/MW by 2050. *Alkaline* • Nickel: 3.2 t/MW, falling to 2.6 t/MW by 2050.	• Fuel cell efficiency reaches 55/60% by 2040/50 (vs. 50/55%). • Alkaline market share rises to 30% by 2050 (vs. 10%). • Faster and greater reductions in materials intensity of nickel, platinum, palladium.	• 70/90% of electrolysers collected for recycling at end of life by 2040/50. • Platinum end-of-life recycling rate reaches 75/90% by 2040/50.
CCS/DAC	**Sorbent Requirements** • *DAC:* 7.5 kg of MEA/tCO_2 captured, falling to 3 kg/tCO_2 by 2050. • *CCS:* 0.5 kg of MEA/tCO_2 captured, falling to 0.4 kg/tCO_2 by 2050.	• N/A	• N/A

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