The **Barriers to Clean Electrification** Series

Material and Resource Requirements for the Energy Transition

Executive Summary

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:

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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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1. A clean energy system, centred around clean electrification, requires rapid deployment of clean energy technologies this decade and beyond

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.[1] Key features include [Exhibit 1]:[2]

- **A dramatic increase in global electricity use,** rising from ~28,000 TWh in 2022, to as much as ~110,000 TWh by 2050, with over 75% of this supplied by wind and solar. The rest will be provided by a mix of nuclear, hydropower and other zero-carbon sources, along with battery and other storage.
- **A major expansion of electricity grids,** expanding from the current ~75 million km of transmission and distribution lines to over 200 million km by 2050.
- **A major role for low-carbon hydrogen,** growing from 90–100 Mt of annual consumption today (of which only ~1 Mt is low-carbon) to 500–800 Mt per annum, of which ~85% will 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 vehicle fleet by 2050,** requiring ~1.5 billion electric passenger 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.

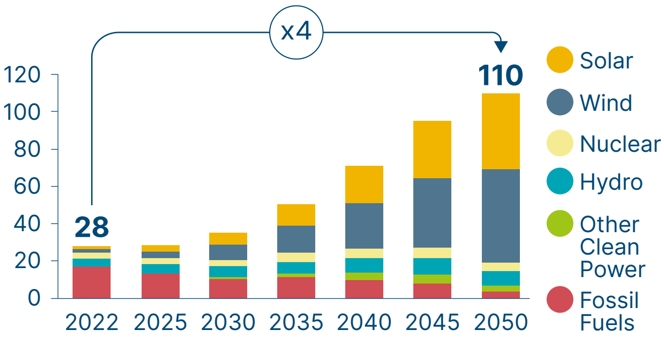
1 ETC (2020) *Making Mission Possible*; ETC (2021) *Making Clean Electrification Possible*; ETC (2021) *Making the Hydrogen Economy Possible*; ETC (2022), *CCUS in the energy transition: vital but limited.*

2 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.

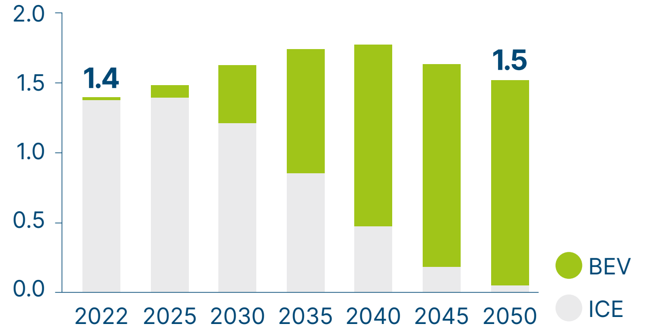
EXHIBIT 1

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

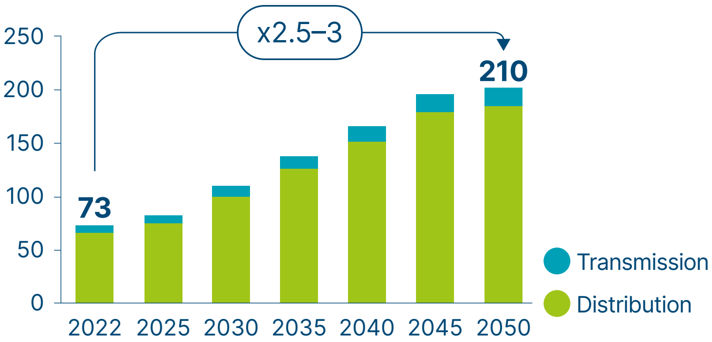
Electricity generation
1000s of TWh/year



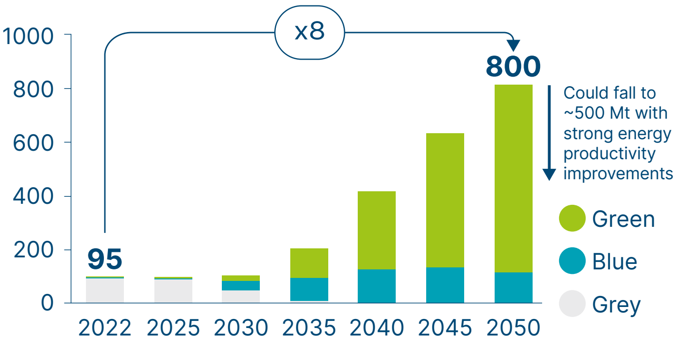
Passenger vehicle fleet
Billions of vehicles



Total transmission and distribution power line length
Millions of km



Hydrogen production
Mt/year



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

Achieving this will require a major increase in investments in clean energy, overcoming multiple barriers to implementation, and the development of expanded supply chains for clean energy technologies. The ETC has therefore this year focused on how to overcome potential barriers to clean electrification, with reports already published on finance and investments for the energy transition, clean energy supply chains, planning and permitting, and a forthcoming report on power grids.[3] This report focuses specifically on the material resources required for the energy transition.

This report's overarching message is that there are plentiful resources available to support a prosperous net-zero global economy. A zero carbon energy system will have massively reduced environmental impacts than today's fossil fuel system; however, strong policies and actions are required to address specific challenges.

Key points are that:

- The new clean energy system will have **manageable requirements for land and water**, and producing the materials required for it will result in cumulative lifecycle emissions which are trivial compared to those produced by the fossil fuel-based energy system.

- There are **sufficient raw materials** to support the transition, particularly given opportunities for innovation and recycling to reduce material requirements.

3 ETC (2023), *Financing the Transition: How to Make the Money Flow for a Net-Zero Economy*; ETC (2023), *Streamlining planning and permitting to accelerate wind and solar deployment*; ETC (2023), *Better, Faster, Cleaner: Securing clean energy technology supply chains.*

- **Scaling supply** rapidly enough to meet demand growth between now and 2030 will be challenging for some metals, and mining will need to expand significantly.
- Policymakers and industry must ensure a fast, sustainable increase in supply by:
  - **Scaling up mining** and refining capacity.
  - Addressing issues relating to **diversity and security of supply.**
  - **Addressing environmental and social impacts of materials production.**
  - Driving **materials and technology efficiency and recycling** to minimise long-term primary resource needs.

2. Manageable land and water requirements; trivial emissions from materials production compared to fossil fuel based system

Building and operating a clean energy system will require land and water use on a scale comparable with today's fossil fuel-based energy system, but both systems require trivial land and water inputs compared with global agriculture [Exhibit 2]:

- **Land** to site solar and wind farms for power generation, including for green hydrogen production and direct air capture of carbon dioxide (DACC) could amount to 0.4–1.1 million km^2, or around 1% of global habitable land area.[4] In many cases this land use could be co-located with other uses, such as solar PV on buildings, or wind on working farms. Almost all future bioenergy can and should be met from waste and residues, with zero to minimal additional land used to grow crops relative to today.[5] This is a larger land requirement than required by the fossil fuel based system (around 0.2–0.4 million km^2), but very small compared to the 51 million km^2 of land devoted to agriculture.[6] Deforestation is predominantly driven by agriculture,[7] and biodiversity losses are overwhelmingly driven by land-use change for food production, or by climate change impacts induced by use of fossil fuels.[8]
- **Water** for power generation, hydrogen electrolysis and carbon capture could amount to around 58 billion m^3 per year, predominantly driven by nuclear power (14 billion m^3) and water for carbon capture (19–29 billion m^3). Mining for the energy transition could increase this amount by a further 4–5 billion m^3. The total requirement is the same order as magnitude as the approximate 37 billion m^3 per year required for fossil fuel extraction and power generation,[9] but is less than 2% of total human global water consumption of around 4,000 billion m^3 each year, of which about 70% is used in agriculture.[10]
- Building a zero carbon energy system will also result in some one-off **greenhouse gas (GHG) emissions**: the first generation of renewable energy generating equipment must inevitably be manufactured using today's energy mix, which in many parts of the world still predominantly relies on fossil fuel based energy. But the total lifecycle CO_2 emissions resulting from producing the requisite materials amount to around 15–35 GtCO_2e over the next 30 years, compared with around 41 GtCO_2e produced *every year* from the current fossil-fuel based energy system.[11] These emissions will fall close to zero over time, as the emissions associated with mining and materials production themselves fall to zero, whereas fossil fuel emissions would continue at 41 GtCO_2e per annum forever if a zero carbon energy system is not built.

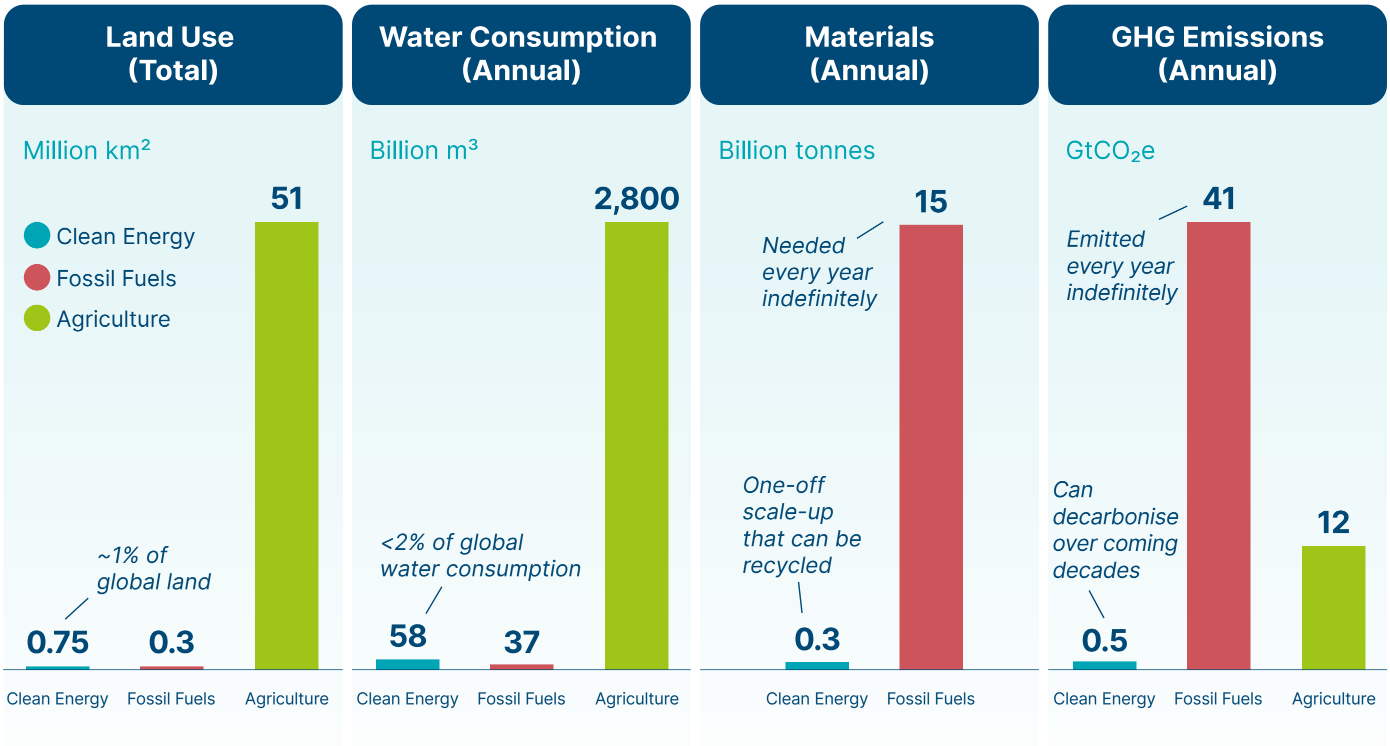
Neither global land and water requirements, nor the lifecycle emissions entailed in producing materials for a zero carbon energy system, are therefore valid arguments against building that system as rapidly as possible. But land and water constraints may be important in specific densely populated and water stressed regions, and the local environmental impacts of mining will require careful management.[12]

4 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*.
5 ETC (2021), *Bioresources within a Net-Zero Emissions Economy.*
6 See Chapter 1, Section 1.1.1 in the main report, and also Our World in Data (2019), *Land use*.
7 ETC (2023), *Financing the transition: Supplementary report on the costs of avoiding deforestation.*
8 Jaureguiberry et al. (2022), *The direct drivers of recent global anthropogenic biodiversity loss*; IPBES (2023), *Models of drivers of biodiversity and ecosystem change*.
9 IEA (2016), *Water-energy nexus.*
10 Our World in Data (2017), *Water use and stress.*
11 See Chapter 4, Section 4.1 in the main report, and also IEA (2023), *CO_2 emissions in 2022*. GHG emissions from the energy system were 41 GtCO_2e in 2022, including emissions from industrial processes and waste. The IEA data assumes a GWP100 value of 30 for methane.
12 These issues are discussed in detail in Chapter 4 of the main report.

EXHIBIT 2

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	Water Consumption	Materials	GHG Emissions
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.
Agriculture	Current land use for agriculture including crops and livestock for meat and dairy.	Current water consumption for all agriculture.	N/A – 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, *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*.

3. Easily sufficient resources to meet material demand

Different clean energy technologies will drive future demand for different materials [Exhibit 3]:

- **Industrial materials** such as steel, copper and aluminium are required across most of the clean energy technologies; and demand for these is also driven by a wide range of other non-energy related industrial or consumer uses, such as steel for construction or copper for electronic products.
- In other cases, specific **clean energy technologies drive specific material needs** (e.g., cobalt for batteries and polysilicon for solar panels), and the energy transition is the dominant driver of total demand for these materials.

EXHIBIT 3

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	–	Mid	–	Mid	Construction, transport, industry, beverages
Cobalt	–	–	–	High	–	–	–	Consumer electronics, steel alloys
Copper	High	High	High	High	High	Mid	Mid	Industry, construction, electronics, wiring
Graphite (for Anodes)	–	–	–	High	–	–	–	Steel production, lubricants, pencils
Lithium	–	–	–	High	–	–	–	Consumer electronics
Neodymium	–	High	–	High	–	Mid	–	Magnets for industry, consumer electronics
Nickel	–	Mid	–	High	High	Mid	Mid	Steel alloys
Palladium and Platinum	–	–	–	–	High	–	–	Auto catalysts
Polysilicon	High	–	–	–	–	–	–	Alloys, lubricants, semiconductors
Silver	High	–	–	–	–	–	–	Jewellery, industry, investment
Steel	High	High	High	–	High	High	High	Construction, transport, consumer goods
Uranium	–	–	–	–	–	High	–	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. 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.*

In total, between 2022 and 2050, the energy transition could require up to 6.5 billion tonnes of materials, cumulatively, of which 95% is accounted for by steel, copper and aluminium. By contrast, some other material needs are small in tonnage terms but critical to the production of specific clean energy technologies. The total stock of pure lithium required in all electrical vehicles between now and 2050, for instance, is likely to be around 20 million tonnes.[13] These numbers compare with today's annual coal extraction of over 8 billion tonnes.[14]

There are sufficient existing mineral resources[15] available on land to meet future demand through to 2050 [Exhibit 4].[16] Known mineral resources far exceed the total cumulative demand for key materials required for both the energy transition and all other uses from now to 2050.[17] Past experience has shown, moreover, that as demand rises new resources and reserves are identified.

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" would be insufficient to meet cumulative demand from the energy transition (in a situation where demand rose rapidly but there was limited progress in technology and materials efficiency and recycling) together with other sectors. Under such a scenario reserves might need to expand by up to 30% for copper, 70% for nickel, and 90% for silver to meet total expected demand between 2022–50 [Exhibit 4].

But turning resources into reserves is not expected to be a major challenge: a combination of economic incentives, technological progress and increased exploration tends to drive expansion in estimated reserves over time.[18]

13 See Chapter 1, Section 1.2.2 and Chapter 2, Section 2.3.3 in the main report.

14 IEA (2022), *Coal 2022*. See Chapter 1, Section 1.3.2 and Chapter 4, Section 4.2 in the main report for discussion of waste rock produced by mining.

15 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.

16 There are also resources available in the deep sea for certain materials, notably nickel and cobalt. Given that land-based resources are sufficient to meet future materials demand, exploiting deep sea resources would be a choice, with associated trade-offs (just as there are strong trade-offs for land-based mining). Any future deep-sea mining should proceed with strong caution and high standards for environmental impacts. The topic of deep sea mining is discussed in Box G in the main report.

17 Mineral resources are from USGS (2023), *Mineral commodity summaries*.

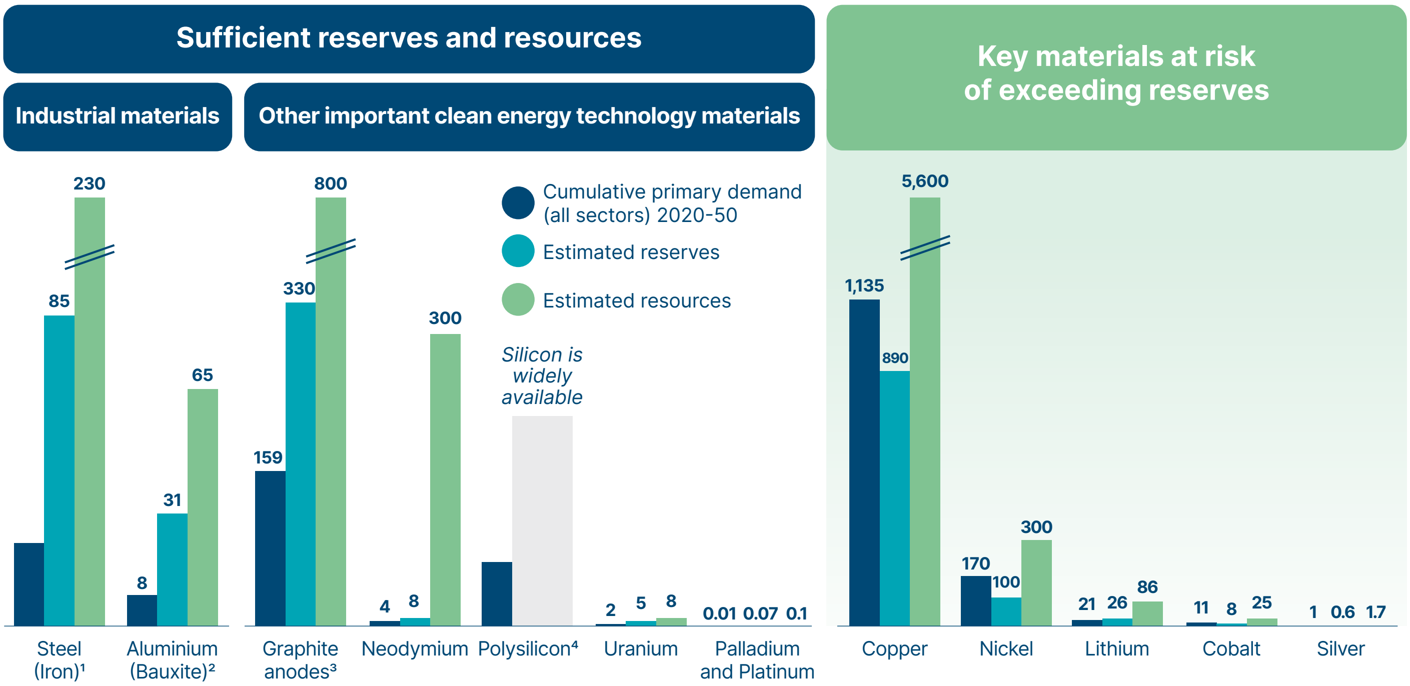
18 For example, reserves of copper expanded from 690 Mt to 880 Mt between 2013–21, even as annual production grew from 18 Mt per annum up to 21 Mt per annum. US Geological Survey.

EXHIBIT 4

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, 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.

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.

Furthermore, technology and materials efficiency and improved recycling can significantly reduce the amount of primary material needed in clean energy technologies [Exhibit 5], by 20–60% for most materials. Three of the most promising areas of action are:

- Rapid evolution of **battery chemistries** leading to much lower future demand for cobalt and nickel. Projections for cobalt demand in 2030 have already fallen by 50% over the last 5 years following the rapid development of low-cobalt NMC and cobalt-free LFP batteries.[19]

- A smarter, more highly-digitalised **transmission and distribution grid** that is better able to integrate wind and solar can help limit the overall scale of grid build-out that is required – reducing demand for copper and aluminium.[20] Alongside this, substitution of aluminium in place of copper, especially in overhead lines, could reduce annual demand for copper by around 0.5–1 Mt each year.[21]

- The increasing size of on- and off-shore **wind turbines** and the rising efficiency of **solar PV**, both of which are driving down material intensity per gigawatt of installed capacity, and per terawatt-hour of clean electricity produced.[22]

19 NMC = nickel-manganese-cobalt; LFP = lithium-ferrous-phosphate. BNEF (2022), *Long-term electric vehicle outlook.*

20 DNV (2022), *Future-proofing our power grids*; BNEF (2023), *New energy outlook: Grids.*

and aluminium compete to build the future power grid.

22 However, this is posing some increased logistical challenges for installation. See ETC (2023), *Better, faster, cleaner: Securing clean energy technology supply chains.*

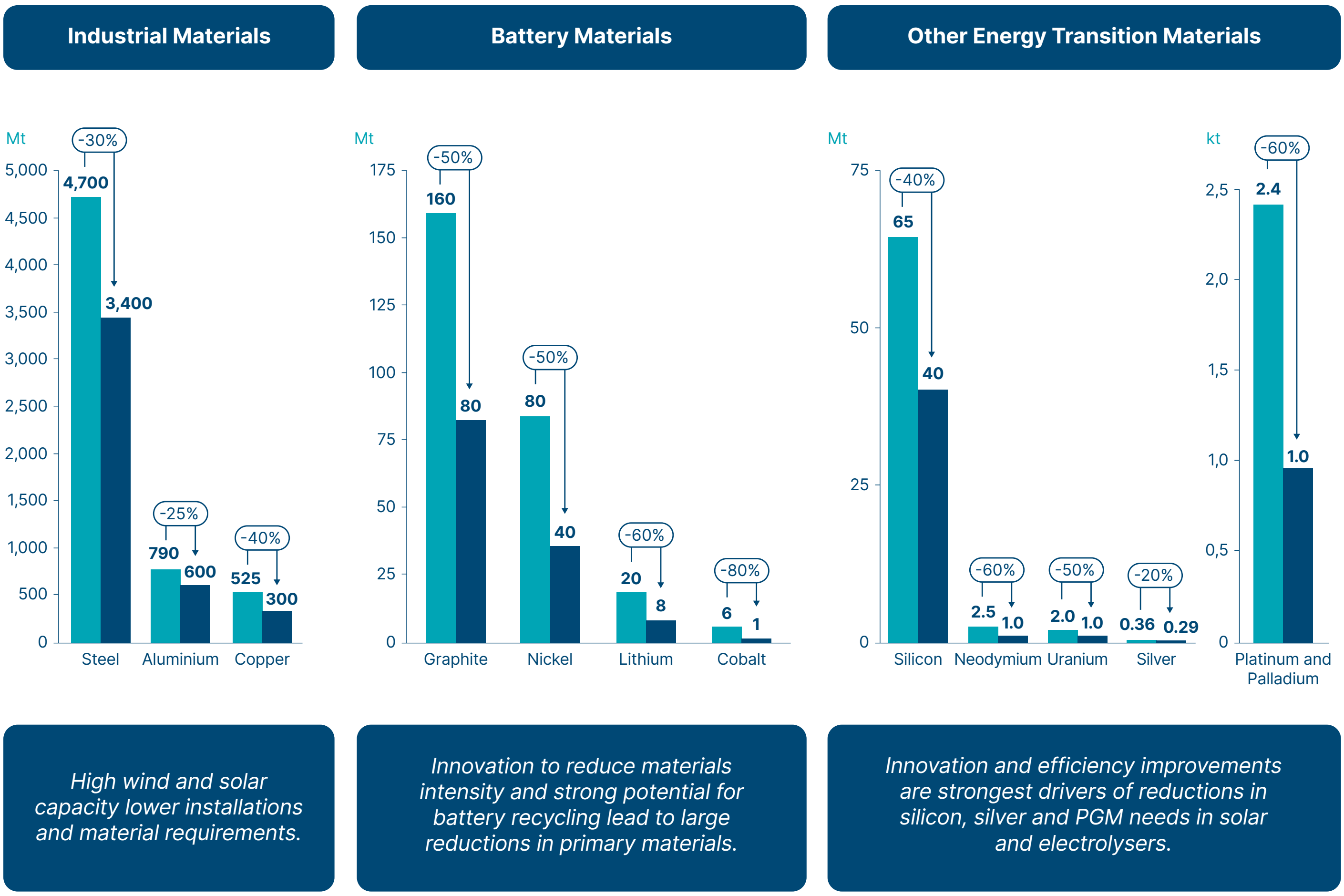
EXHIBIT 5

Efficiency and recycling can reduce primary material requirements significantly – but more innovation and policy support 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)

Baseline Decarbonisation
Maximum Efficiency and Recycling



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.

4. Rapid demand growth could lead to supply shortages and high prices over the next decade

Rather than long-term resource adequacy, the key issue relating to material and mineral supply is whether supply can be expanded rapidly enough over the next decade to avoid constraints on the feasible pace of clean technology deployment.

Exhibit 6 compares a range of 2030 demand estimates for six key energy transition minerals with the supply that would result given existing mine capacity plus already announced plans for mine expansion or new mine development. In each case, we show current supply, demand in 2030 under a scenario where demand rises rapidly but materials intensity and recycling continue along existing trends, and how much the 2030 demand could be reduced via maximum feasible progress in technology and materials efficiency and recycling.

The key implications are:

- In each case, there will be dramatic **demand increases** by 2030, with the pace of growth in some cases far faster than seen before in minerals markets.
- Even over the period to 2030, the increase in demand could be significantly reduced via strong action to accelerate **technical innovation and recycling** [Box A]:
    - Such action could conceivably close the demand/supply gaps almost entirely for nickel and copper – although achieving this for copper will be especially challenging, given its widespread use across many clean energy technologies.
    - For graphite, cobalt, lithium and neodymium, although efficiency and recycling measures would help reduce supply gaps significantly, current supply pipelines would still fall short.

The implication is that mining supply will need to expand to meet 2030 demand, and in some cases will need to expand still further in subsequent years. In many cases, a large share of increased demand can be met from existing mines: for example, in the case of copper increased utilisation rates and operating efficiency could yield around 3 Mt of additional output, out of a required 8–9 Mt increase by 2030 (around 35%).[23] However, the majority of increased supply will need to be met by new mines: in total across all the minerals in Exhibit 6, up to 250 new mines could be required.[24]

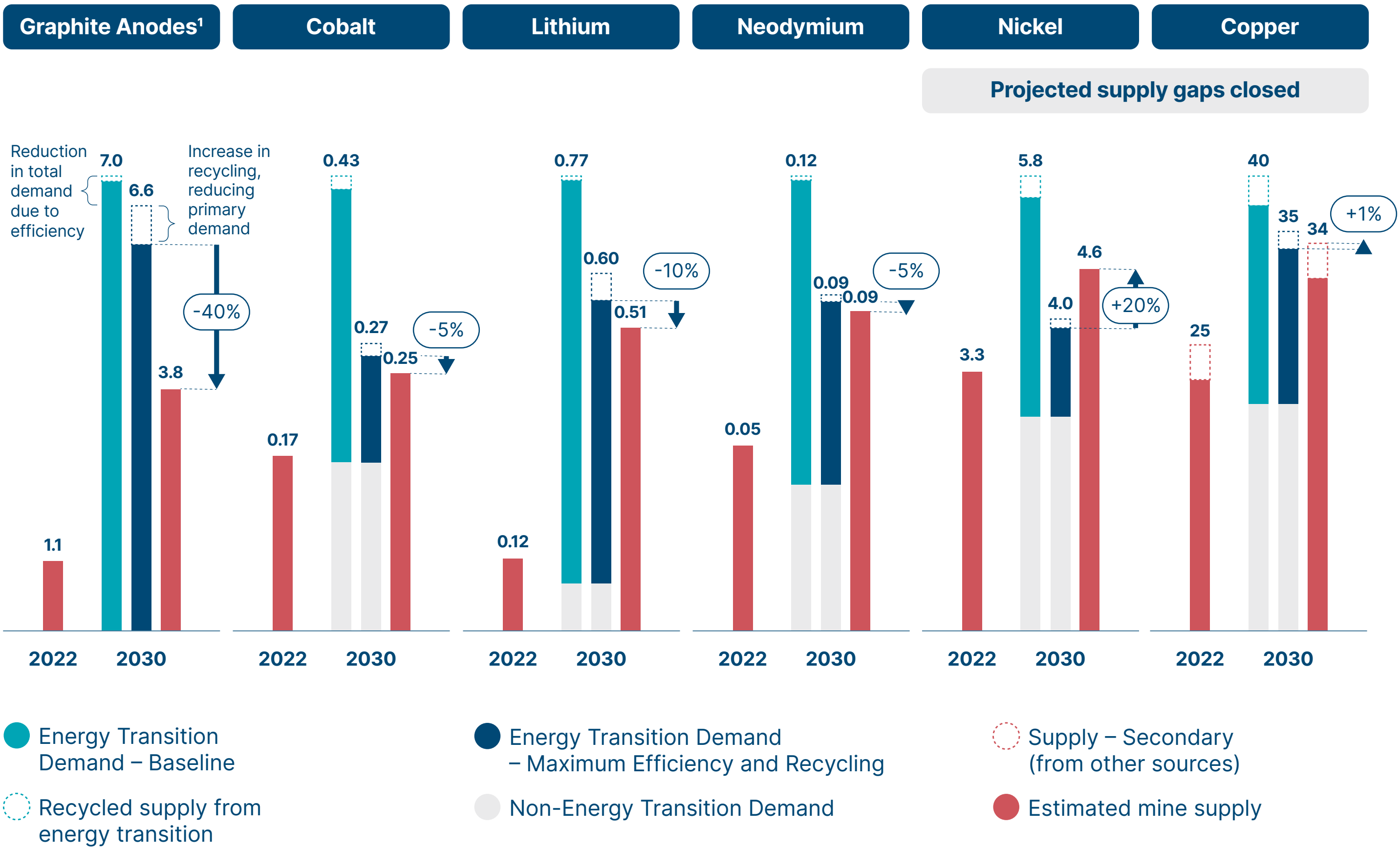
23 Based on utilisation rates and supply scenarios in S&P Global (2022), *The future of copper.*

24 See Chapter 2, Section 2.4.3 in the main report, and also IEA (2023), *Energy technology perspectives*; Benchmark Mineral Intelligence (2022), *More than 300 new mines required to meet battery demand by 2035.*

EXHIBIT 6

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.

BOX A: The importance of recycling – of batteries in particular

Secondary supply of recycled materials can and must play a crucial role in reducing primary material requirements. By the late 2040s:

- 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% beyond 2030.

- In the case of **copper or aluminium**, secondary supply could meet 30–40% of energy transition demand. For both materials, and especially for copper, there is also strong potential to expand recycling of copper used in other non-energy related sectors.

- For **other materials**, such as silicon, 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.

Over the shorter term to 2030, however, recycled secondary supply of most minerals cannot meet more than around 10% of demand,[25] since the number of clean energy technology products (e.g., batteries in EVs) reaching end of life will be small relative to annual demand. But it is essential to impose strong end-of-life recycling requirements, and make anticipatory investments in logistics and infrastructure, to drive a steadily rising share of secondary recycled supply in subsequent years.

For wind turbines and solar panels, large-scale recycling is feasible and should be strongly encouraged – but landfill volumes would be 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.[26] 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.[27] Similarly for solar panels, over 90% of materials can be recovered and recycled or re-used in other sectors.[28]

- 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.[29] 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.[30]

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 nickel-manganese-cobalt batteries (which include cobalt and nickel as well as lithium) extensive recycling would occur even without regulation; by contrast lithium-iron-phosphate batteries (where only the lithium is highly valuable), might not be fully recycled without strong regulation or initial subsidies.[31]

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 Section 5, Point iv.

25 See Exhibit 2.13 in main report.
26 Wind Europe (2020), *Accelerating wind turbine blade circularity.*
27 Ibid.
28 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?*
29 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.*
30 World Bank (2018), *Trends in solid waste management.*
31 Lander et al. (2021), *Financial viability of electric vehicle lithium-ion battery recycling.*

5. Four key challenges must be overcome to scale supply quickly and sustainably

The key to meeting material requirements for the energy transition at the pace required is 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.

Policymakers, mining companies, and the rest of the material value chain must therefore act to achieve four objectives:

i. Rapid scale-up in supply

Balancing supply and demand has always been difficult in commodity markets, with strong price swings frequently observed as demand increases faster than supply can respond or as investment in new supply creates overcapacity. Recent dramatic volatility in the price of both polysilicon and lithium carbonate illustrate this tendency and similar swings will inevitably occur in future.[32] But six actions can at least help induce a smoother and adequately rapid growth in supply:

- **Build new mines and expand existing supply of materials quickly:** The ETC's analysis in the main report shows that output equivalent to hundreds of new mines will be needed in the coming decade.[33] Some of this can be met by existing mines, but a large amount will need to come from new mining projects beginning production.

- **Providing maximum clarity around future demand.** The rapid pace of clean energy technology deployment, fast innovation timescales, and the small size of markets for many critical minerals, together lead to major revisions in demand projections over short periods of time, creating uncertainty for investors. Public policy can at least reduce these uncertainties by setting clear targets for the deployment of key clean technologies. This should entail quantitative targets for wind and solar capacity deployed by specific dates, legislated dates for the complete phase-out of internal combustion engines, and clear strategies for grid development supported by regulatory frameworks which allow grid companies to invest ahead of future demand.

- **Accelerating mining timescales.** New large-scale mines can take up to 15–20 years to begin production [Exhibit 7]. These can be shortened by accelerating permitting timescales, making financing and power access available earlier, and ensuring local regulators have adequate staffing and funding in both developed and developing countries. Such accelerated permitting should not be at the expense of adverse environmental and social impacts, but should be ensured for projects which have clear plans for meeting high standards. Since timescales for developing new refining capacity are typically shorter, and refinery location is not limited by resource location, new capacity can typically respond more easily to growing demand – but, as with mining, rapid development should go hand-in-hand with strong environmental standards.

- **Increasing public and private finance for high-priority developments.** Non-ferrous capital spending has averaged around $45 billion each year over the last two decades, well below the $70 billion needed yearly through to 2030 to expand supply. Significant investments in processing and refining capacity, of $70–100 billion each year through to 2030, will also be needed.[34] Achieving this will need investors to understand the important role metals mining and refining must play in the energy transition – investing in gigafactories is not enough. Development finance institutions can also help finance and de-risk projects in lower-income countries, whilst pushing for strong standards on sustainable and responsible mining.

- **Increasing mine output,** by improving operational efficiency, optimising when maintenance takes place, investing in digitisation and automation, and commercialising new innovative technologies such as direct lithium extraction or tailings re-processing at scale.

- **Improved data sharing,** including through the publication of open demand and supply forecasts, improved international and industry-government collaboration, and the funding of new and updated geological mapping and surveys.

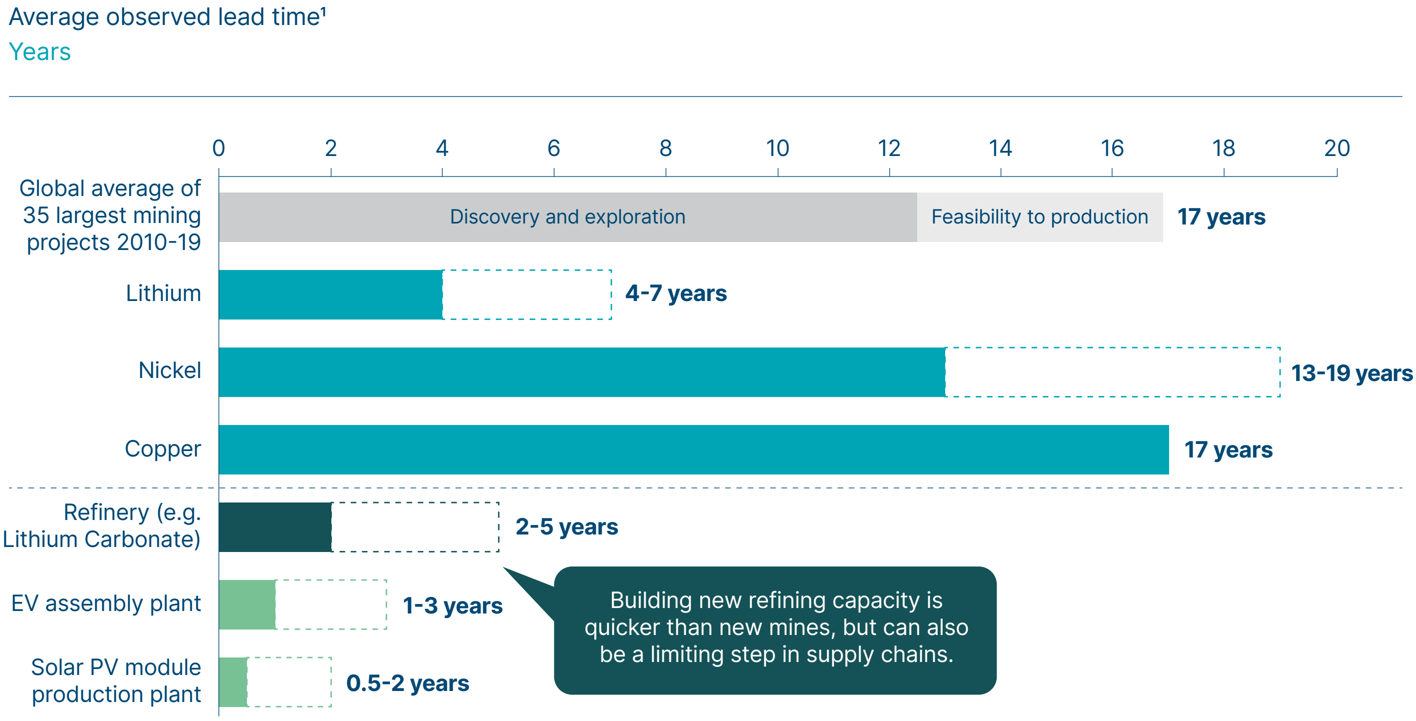
32 See Chapter 3, Section 3.1 in the main report, and also PV Magazine (2023), *Polysilicon prices preserve downward trend, weighed down by supply factors*; Reuters (2023), *Lithium prices bounce after big plunge, but surpluses loom.*

33 See Chapter 2, Section 2.4.3 in the main report for details.

34 Note that these sums include both business-as-usual investment and additional investment required to meet extra energy transition demand. See Chapter 3, Section 3.3.3 in the main report, and 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.*

EXHIBIT 7

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



[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.*

Future demand expectations and recent high prices for several minerals have already stimulated both new resource discovery and new mining projects, including in some developed countries. Large deposits of rare earths have been discovered in Sweden,[35] and of phosphate in Norway,[36] and large lithium deposits are available in Portugal and several other European countries and in several locations in the US. New mining projects in development include the Rönnbäcken nickel-cobalt project in Sweden, the Kathleen Valley lithium mine in Australia and the Kisanfu copper-cobalt mine in the Democratic Republic of the Congo (DRC). More such exploration and mine developments, alongside increased output from existing mines, will be key to meeting growing demand.

ii. Diversify and build resilient and secure supply

The supply of both mined and refined materials is highly concentrated [Exhibit 8]:

- At the **mining** stage, 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. The top six producing countries for copper made up around 60% of production in 2022.

- Concentration is even stronger at the **refining and processing** stages, where China plays a dominant role across five key energy transition materials (cobalt sulphate, copper, lithium carbonate/hydroxide, nickel, and the rare earth elements). This dominance reflects a combination of: China's lower capital, land and labour costs; China's long-standing government support for clean energy industries; and environmental standards which in the past were looser for some refining processes (though with major strengthening recently).

35 Euractiv (2023), *Sweden announces discovery of Europe's biggest deposit of rare earth metals.*
36 The Economist (2023), *A huge Norwegian phosphate rock find is a boon for Europe.*

Previous ETC analysis has also highlighted the strong degree of concentration of downstream clean energy supply chains, especially in the case of solar PV and batteries.[37]

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, especially at a regional or national level; political instability could disrupt supply; and localised issues, ranging from drought to unstable power supply, can knock out supply from a particular region or country.[38]

To mitigate concentration risk, it makes sense for companies and countries to build somewhat more diverse supply chains, reducing reliance on any one country or region. In addition, some countries may perceive it a strategic necessity to ensure that at least a significant proportion of mineral supply comes from domestic capacity or from capacity located in countries which are geographically close or perceived to be strong political allies.

To achieve an optimal role for domestic production or nearshoring, countries will need to:

- **Balance political priorities** relating to local jobs, value-added and security concerns against the increased costs which will often result at least in the short term. This argues for seeking to **diversify and de-risk** supply rather than to attempt a total decoupling which would significantly increase costs and in some cases be physically impossible. The EU's objective to ensure that domestic production meets 10% of demand for mined supply, and 40% of demand for refined supply, of critical minerals reflects this balance.[39]

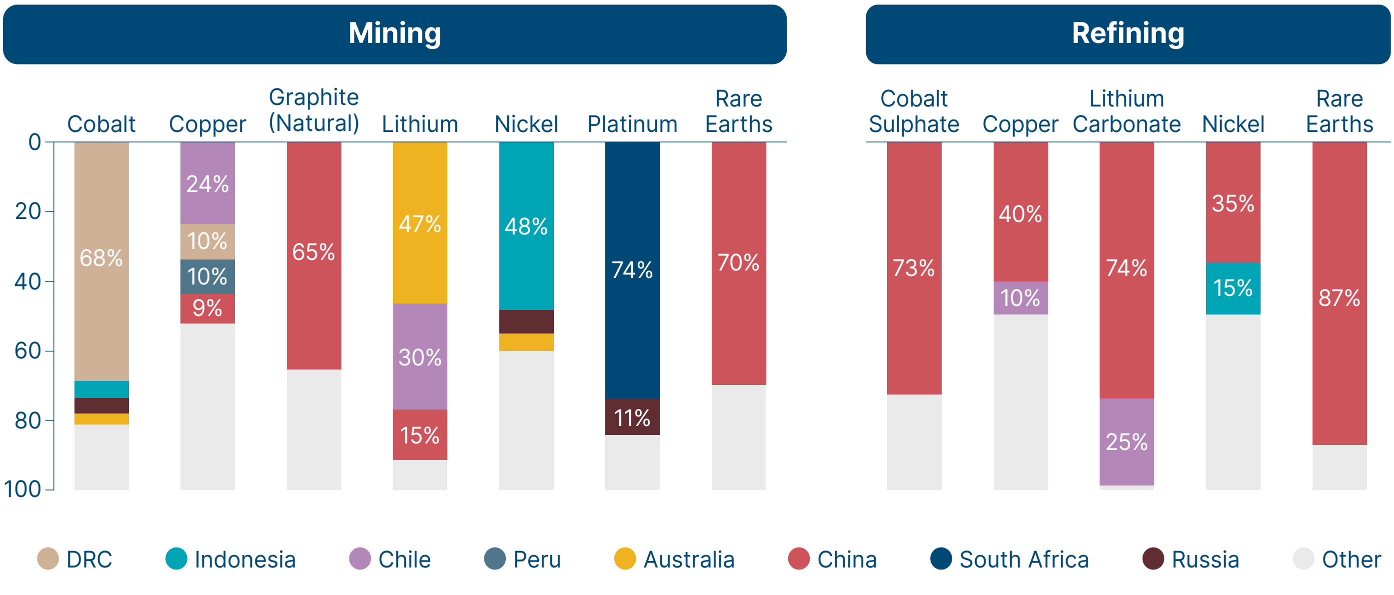
- **Addressing local implementation challenges**, including recognising that increased domestic supply will require planning and permitting systems which allow mine and refinery developments, underpinned by strong environmental standards and by political communication of the positive role that material extraction and refining must play in building a zero carbon economy.[40]

EXHIBIT 8

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.*

37 ETC (2023), *Better, faster, cleaner: Securing clean energy technology supply chains.*

38 IRENA (2023), *Geopolitics of the energy transformation: Critical materials.*

39 EU Commission (2023), *Critical raw materials act.*

40 Trade-offs around diversification and nearshoring are discussed in more detail in ETC (2023), *Better, faster, cleaner: Securing clean energy supply chains.*

iii. Minimising adverse environmental and social impacts

Mining and the production of materials can have significant environmental and social impacts if not carried out in a sustainable and responsible way. These include:

- **Disruptions to local land use:** Although mine sites only occupy around 100,000 km² globally (0.1% of habitable land),[41] local land-use change is significant, driven by the production of large volumes of waste rock and tailings.

- **Biodiversity and nature:** Local land-use change can lead to impacts on deforestation and local ecosystems. Although agriculture is a much larger driver of adverse impacts on biodiversity,[42] indirect impacts of mining on deforestation are significant:[43] one estimate suggests mining could have led to cumulative induced deforestation of up to 760,000 km² between 2001–21, or roughly 38,000 km² each year.[44] However, the vast majority (>70%) of mining deforestation is driven by coal, where impacts will be greatly reduced by the new energy system, and gold, which is not relevant to the energy transition.[45] 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. This compares with total global deforestation running at rate of around 100,000 km² each year.[46]

- **Local toxicity and pollution:** This is a concern if mining or refinery waste is not managed and disposed of appropriately. Tailings dam collapses, acid mine drainage, and impacts from mining and refining on local air quality are all issues of concern.

- **Water consumption:** This is a risk in arid areas (e.g., northern Chile), where mining can exacerbate local water stress and competition for water can lead to tensions with local communities.[47]

- **Impacts on local communities and society:** Although mining can bring significant local economic benefits when done with the consent and trust of local communities, this best practice is not always followed. Poor working conditions and health and safety, human rights abuses, child labour, corruption and tax evasion are all significant risks for mining, especially in jurisdictions with little or poorly-enforced regulation.

These impacts must be addressed for two reasons:

- First, because otherwise the **global benefits** of decarbonisation could come at the expense of **major costs for specific local communities.**

- Second, because future **projects could get delayed or not approved** if developers cannot convince local communities that environmental impacts will be minimised and positive social impact delivered. Recent setbacks in this respect include lithium projects at Thacker Pass in Nevada and Mina do Barroso in Portugal.[48]

To minimise any adverse impacts it is essential to a) reduce the amount of mined materials we need, through increased efficiency and recycling (see Point iv below); b) reduce the impacts per tonne that is mined. To achieve the latter, miners, manufacturers, governments and consumers need to take actions which:

- **Reduce life-cycle emissions of materials and products**, by applying new technologies to mining, refining and manufacturing operations, starting with the decarbonisation of electricity inputs. This should be strongly encouraged and enforced via carbon taxes or pricing and/or strong regulations on the carbon intensity of production, which should apply to imported as well as domestically produced materials or products (for instance via the imposition of border carbon taxes).

- **Manage and mitigate local environmental impacts:** miners must minimise tailings and waste rock production, and impacts on biodiversity and nature, and reduce freshwater consumption as much as possible. Key to this will be focusing on highest-quality ores, to reduce impacts per tonne of final product, and following best practice for sustainable and responsible mining.

- **Engage with local communities** early on and proactively in projects, to obtain their trust and consent for new projects.

- Refiners, manufacturers, governments and consumers can and should **use their purchasing power** to drive demand for supply which meets high environmental and social standards.

- **Define and adopt high-quality environmental and social standards**, and improve and **require supply chain traceability** to help measure, monitor and mitigate impacts throughout supply chains.

41 Maus et al. (2022), *An update on global mining land use.*
42 ETC (2023), *Financing the transition: Supplementary report on the costs of avoiding deforestation.*
43 International Resource Panel (2019), *Global resource use*; Giljum et al. (2022), *A pantropical assessment of deforestation caused by industrial mining.*
44 WWF (2023), *Extracted forests.*
45 Ibid.
46 Our World in Data (2021), *Forests and deforestation*; UN Food and Agriculture Organisation (2020), *Global forest resources assessment.*
47 Meissner (2021), *The impact of metal mining on global water stress and regional carrying capacities.*
48 Inside Climate News (2021), *Plans to dig the biggest lithium mine in the US face mounting opposition*; Mining.com (2022), *Portuguese community files legal action against Savannah Resources.*

Two examples of best-in-class performance on environmental and social impacts could be the new Quellaveco copper mine (discussed in Box I in the main report), 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.

Five priorities are particularly important with regards to ensuring sustainable supply of energy transition materials:

- **Decarbonising steel and aluminium** production, which account for the majority of life cycle emissions resulting from the production of materials for the new energy system, but where clear pathways to total decarbonisation by mid-century can now be described.[49]

- **Reducing use of primary copper**, through substitution or recycling, and making copper mining more efficient to reduce waste, emissions and water per ton produced. This is particularly important since falling ore grades for copper could lead to higher energy and water consumption per ton of copper produced, along with greater volumes of waste rock and tailings.[50]

- **Reducing the emissions intensity of battery materials**, and in particular, lithium and nickel, where increased demand could make future mining and processing approaches more emissions-intensive than the current standard.[51] Here the focus should be on decarbonising mining and manufacturing, whether through renewable power purchase agreements, wider grid decarbonisation, or by focusing on lower-carbon extraction methods.

- **The supply of cobalt from the DRC**, which 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, with widespread reports of human rights abuses.[52] A major area of focus of such concerns is the artisanal and small-scale mining (ASM) sector. Innovation to shift away from cobalt can help reduce demand, 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, leading to highly emissions-intensive production – roughly double what domestic production in the USA or Germany would be.[53] Decarbonisation of China's solar PV (and other) supply chains should therefore be a priority and is feasible given China's world-leading deployment of renewable electricity capacity. 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 relating to both coal mining and polysilicon production.[54] More diverse polysilicon supply chains would be desirable and are feasible given the widespread availability of the raw material inputs in many regions.

iv. Improved technology and increased recycling

Over the long-term, there is very significant potential to reduce primary demand for key materials through technical innovation and recycling [Exhibit 5]. Over the short-term, the potential is more limited but can still help reduce the scale of the challenge [Exhibit 6]. Action on these fronts can help to not only reduce the materials required for the energy transition, but also reduce the size of the challenges outlined above. The fewer materials and technologies are needed, the smaller the increase in mining required and the less reliance there is on concentrated supply.

Industry and public policy should seek to ensure that both short- and long-term opportunities are seized.

Materials and technology efficiency:

- Technological advances have already reduced future demand for cobalt via a shift to low-cobalt NMC and cobalt-free LFP **batteries**. Future potential developments include sodium-ion batteries which have no need for lithium, and (at a later date) lithium-air batteries which would deliver far higher energy density and would replace graphite anodes with lithium-based anodes.

- Innovation is also driving up **solar panel** and **electrolyser** efficiency and **wind** turbine capacity factors, reducing the total number and scale of installations required to meet growing electricity demand and reducing the demand for both minerals and land. Private incentives to achieve increased efficiency are already strong but can be increased further via public support for potential breakthrough technologies.

49 Mission Possible Partnership (2022), *Making net-zero steel/aluminium possible.*
50 Nassar et al. (2022), *Rock-to-metal ratio: A foundational metric for understanding mine wastes*; Calvo et al. (2016), *Decreasing ore grades in global metallic mining: A theoretical issue or a global reality?*; BNEF (2023), *Transition metals outlook.*
51 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.*
52 The Economist (2022), *The world should not ignore the horrors of eastern Congo*; 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.*
53 IEA (2022), *Special report on solar PV global supply chains.*
54 The Breakthrough Institute (2022), *Sins of a solar empire*; Murphy and Elimä/Sheffield Hallam University (2021), *In broad daylight.*

Expectations of future mineral supply constraints, high material prices, and business competition will combine to drive private research and development, but public policy can provide further impetus via tax incentives for R&D, prizes and innovation competitions, and public investments or advanced market commitments to help technologies achieve large-scale deployment.

Recycling and re-use:

Box A described the major opportunities and need for extensive recycling, particularly of batteries. Public policy should encourage or require recycling via:

- **Regulations** which mandate high levels of reuse or recycling of batteries and other products at end of life, and which at a later date (once significant end-of-life supply is available) mandate a steadily rising share of minerals input sourced from recycled material. These regulations should apply to imports as well as to domestic production.

- **Subsidies and incentives** to drive the large scale development of recycling in cases where it may not currently be as economic as for NMC batteries. In the case of solar panels, a subsidy of around $18 per panel could help scale a recycling industry,[55] while a subsidy of $5–20/kWh could make LFP battery recycling economic.[56]

Significant progress is already being made towards strong and appropriate recycling regulations and targets. In the EU, the battery regulation and recycling targets in the Critical Raw Materials Act are well-designed (though might need some clarification and refining)[57] and in China, the Ministry of Industry and Information Technology has issued a series of directives which will drive increased re-use and recycling of batteries.[58] The US Inflation Reduction Act also includes tax credits for projects associated with "industrial or manufacturing facilities for production or recycling",[59] but these incentives should be reinforced by targets and requirements for collection at end of life and/or minimum recycling recovery rates.

In designing public support policies for both technology and materials efficiency and increasing recycling, one key criteria should be potential to reduce demand for minerals where supply constraints or adverse local environmental impacts are most likely to be significant.

55 Walzberg (2021), *Role of the social factors in success of solar photovoltaic reuse and recycle programmes.*
56 Lander et al. (2021), *Financial viability of electric vehicle lithium-ion battery recycling.*
57 The CRMA includes a target of 15% of demand in 2030 to be met by recycled supply for a range of critical raw materials. EU Commission (2023), *Critical raw materials act.*
58 Electrive (2022), *Battery reuse & recycling expand to scale in China.*
59 Bipartisan Policy Center (2022), *Inflation Reduction Act Summary: Energy and Climate Provisions.*

6. Cross-cutting risk assessment for materials and technologies

Bringing together analysis of the challenges around increasing demand, the potential for innovation and recycling, concentration of supply, and environmental and social impacts, leads to a focus on six key materials [Exhibit 9].

EXHIBIT 9

Material	Clean Energy Technologies	Key Challenges	Priority Actions
Cobalt	Batteries/EVs	• Annual demand for cobalt could increase 2–3x by 2030. • Cobalt is typically mined together with either copper or nickel. Uncertainty over supply from DRC (~70% of market and concerns around human rights), but strong supply growth from Indonesia. • Trend away from cobalt-rich batteries will ease supply imbalances. • High potential to increase recycling from EV batteries.	• Accelerate development of low- or cobalt-free batteries. • Improve labour standards for artisanal and small-scale mining. • Scale use of supply chain transparency. • Diversify mining and refining.
Copper	Grids Wind Solar Batteries/EVs Electrolysers Nuclear	• Annual demand for copper could increase by 1.4–1.6x by 2030. • The world's largest copper producer is Chile (30% of production). Declining production from existing mines, falling ore grades, up to 20 years for new large mines to come online. • High prices will incentivise thrifting or substitution, but widespread need limits potential for large demand reductions.	• Substitute, thrift and reduce copper demand, and scale copper recycling from existing stock in-use – driven by high prices. • Focus on highest-grade copper deposits, to reduce waste rock, energy and water intensity.
Graphite	Batteries/EVs	• Annual demand for graphite could increase 6–7x by 2030. • Graphite anodes can be produced from natural (mined) graphite, or from synthetic graphite (from fossil fuel processing). • Natural graphite supply dominated by China, but new projects in US and Africa. • 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.	• Incentivise adoption of smaller cars and batteries. • Accelerating anode doping with silicon, and/or shift to lithium-metal anodes. • Improve technical recycling rates. • Diversify and decarbonise production of synthetic graphite.
Lithium	Batteries/EVs	• Annual demand for lithium could increase 5–7x by 2030. • Lithium can be extracted by evaporation from brines (South America) or by mining hard rock (Australia). Some concerns around current water and carbon intensity of mining/refining. • 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 recycling potential over long-term.	• Incentivise adoption of smaller cars and batteries. • Accelerate adoption of sodium-ion batteries. • Improve technical recycling rates. • Accelerate development of direct lithium extraction from brines. • Diversify refining.
Neodymium	Wind EVs	• Annual demand for neodymium could increase by 2–3x by 2030. • China dominates the mining (70%) and refining (85%) of rare earth elements, but potential new supply in Myanmar, USA, Australia. • Potential to reduce material intensity and shift to neodymium-free motors. • Mining and refining generate large volumes of toxic waste and historically poorly regulated.	• Shift EV motors to rare-earth free motors. • Reduce rare earth intensity of wind turbine designs (in part driven by larger, more efficient turbines). • Diversify mining and refining to regions with higher standards.
Nickel	Batteries/EVs	• Annual demand for nickel could increase by 1.4–2x by 2030. • The world's largest producer is Indonesia (50%), although Russia also produces a large proportion of high-purity Class 1 nickel – the kind used for EV batteries. Current Indonesian production is carbon intensive. • Tight supply high quality Class 1 nickel and refined nickel sulphate for battery cathodes. • Strong potential to shift away from nickel-rich batteries.	• Accelerate development of nickel-free batteries. • Decarbonise power supply for nickel mining and refining in Indonesia.

A cross-cutting assessment of the risks for rapid deployment of clean energy technologies, including the materials-specific challenges outlined above, leads to the conclusion that risks from materials supply are highest for batteries and electric vehicles:

- **Batteries and EVs are the technologies 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 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. Such supply risks could slow down battery price declines, leading to more expensive electric vehicles, delayed adoption, and higher emissions from road transport.[60]

- **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.[61]

- The build-out of **transmission and distribution grids** could face challenges from high copper prices – although there is some potential for improved efficiency and substitution, as outlined above. Challenges to grid scale-up are more likely to manifest in terms of grid build-out timescales.[62]

- Other clean energy technologies may face more minor, specific challenges to material supply but these are unlikely to significantly delay deployment.

7. Building an inherently more sustainable energy and materials system – key actions for policy makers and industry

The new energy system based primarily on zero carbon electricity will be dramatically and inherently more sustainable than the old one based on fossil fuels. While in the old system, fossil fuels need to be extracted and combusted continuously and in perpetuity, in the new one, minerals are used to build durable assets to generate and use electricity, and can be recycled to a large extent at end-of-life. As a result, the total cumulative emissions produced in building a zero carbon energy system will be far less than the annual emissions of the fossil fuel based system, which are driving potentially catastrophic climate change. And the land use and water requirements are a trivial fraction of those imposed by the agricultural system at a global scale.

But extracting minerals and making the materials to build this new system will require land and water resources which are significant in specific locations and will impose local environmental impacts which must be managed and minimised. And while available mineral resources greatly exceed long-term requirements, growing supply rapidly enough to meet the expected demand growth over the next decade will be challenging for some minerals.

Governments, regulators, consumers and producers must therefore take actions which achieve four objectives:

- **Alleviate pressure on primary supply**, by accelerating technology and materials efficiency and scaling recycling across clean energy technologies and materials.

- **Build new mines and expand supply**, by creating clarity on future demand, reducing mine development timescales, increasing financing for mining and refining, boosting mine production, and improving international collaboration and data-sharing.

- **Diversify and secure sources of supply** over the short- to mid-term, to reduce risks from concentration of supply, and carefully weigh up the costs and potential benefits of near-shoring of supply.

- **Mitigate environmental and social impacts** through strong regulation, backed by widespread use of voluntary standards and supply chain traceability – and driven by best-in-class actors in the mining sector.

60 See Chapter 5, Exhibit 5.2 in main report for an illustration of magnitude of these effects.
61 ETC (2023), *Streamlining planning and permitting to accelerate wind and solar deployment.*
62 This topic will be covered in detail in an upcoming ETC report on Grids in the Energy Transition. See e.g., Financial Times (2023), *Grid bottlenecks delay transition to clean energy.*

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