



International
Resource
Panel

IRP Co-Chair Opinion Piece

ENABLING THE ENERGY TRANSITION

**Mitigating growth in
material and energy needs,
and building a sustainable
mining sector**

*Implications for Transition
Material management*



I ACKNOWLEDGMENTS

Authors: Janez Potočnik and Izabella Teixeira.

The authors of this piece would like to thank Systemiq (Jakob Franke, Rebecca Nohl, Julia Okatz and Arthur Neeteson) and the International Resource Panel (IRP) Secretariat (Merlyn van Voore, Ainhoa Carpintero Rogero, Hala Razian and Christina Bodouroglou) for their support in the development of this piece. They thank the SUN Institute Environment & Sustainability for its vital in-kind support. For their review and other valuable input, they also thank the IRP panel and Steering Committee members.

Recommended citation: IRP (2023). Enabling the energy transition: Mitigating growth in material and energy needs, and building a sustainable mining sector. Potočnik, J., Teixeira, I. An Opinion Piece of the International Resource Panel Co-Chairs

Design and layout: Txabi Jones

Copyediting: Carolyn Boyle

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About this piece

- This is an opinion piece from the Co-Chairs of the International Resource Panel (IRP), Janez Potocnik and Izabella Teixeira.
- It presents the IRP Co-Chairs' perspectives on achieving decoupling while managing future demand for energy transition materials and mitigating their environmental impact. It also suggests the direction of future scientific research in this field and makes recommendations for immediate multilateral and national policy actions.
- The opinion piece builds on existing and upcoming IRP research on future demand for transition materials and their environmental impact – most significantly, the forthcoming *Global Resources Outlook 2024 (GRO24)*. Where upcoming IRP work is referenced, the precise data may potentially be subject to peer-review related changes, but the direction of the findings is highly likely to remain.
- In addition to existing and forthcoming IRP research, this piece draws on other energy transition expertise, such as research by the International Energy Agency (IEA) and the Energy Transitions Commission (ETC). The piece is also informed by the analysis and perspectives of energy industry practitioners, as the IRP Co-Chairs recognise the importance of the industry's own views on future risks and opportunities. Where mentioned, industry perspectives are marked as such.



Janez Potočnik and Izabella Teixeira

Co-Chairs of the International Resource Panel



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I KEY MESSAGES

- **Reaching net-zero greenhouse gas (GHG) emissions is a global priority in the fight against climate change;** and the energy transition is essential to achieve this goal.
- **Human wellbeing must be decoupled from resource use to address the triple planetary crisis of climate change, biodiversity loss and pollution.** Unchecked material extraction and processing are resulting in severe biodiversity loss and water stress, driving GHG emissions and causing pollution-related health impacts.
- Decoupling will also accelerate and facilitate the energy transition. However, the energy transition depends on key materials including lithium, copper, cobalt and nickel. Without systemic efficiency measures, demand for copper, cobalt and nickel could rise by 350% in the next decade, while demand for lithium could soar by 1200% by 2050.
- **This exponential demand could jeopardise the energy transition,** as scaling supply is a complex and lengthy process. Further challenges include environmental impacts, human concerns and high geographical concentration, which makes the global supply of transition materials vulnerable to local shocks. Investment of up to \$1.7 trillion will be needed for the extraction, refining and secondary supply of transition materials by 2050, presenting significant opportunities for source countries.
- The associated risks can be minimised and the opportunities maximised through **strategic management of transition materials based on three pillars:**
- **Pillar 1: Mitigate the underlying drivers of demand for transition materials:** Social wellbeing can be delivered using less energy and fewer materials. The overall feasibility of the energy transition can be improved by optimising material and energy-intensive systems (eg, mobility, housing, nutrition). According to *GRO24*, optimising these systems could reduce global energy demand by around 50% by 2060 (compared to business as usual); while optimising mobility could reduce overall annual copper demand for transport applications (eg, cars, trains, bicycles) by around 60% within the same timeframe.
- **Pillar 2: Apply all circular economy levers to transition materials and technologies that contain them:** The value and function of each extracted unit of transition materials should be maximised across the whole lifecycle. Today, just 1% of lithium is recycled: there is thus abundant potential to design technologies for recycling and establish a reliable secondary supply. Repair, lifespan extension and more intensive use are all important levers in this regard. However, even if all these levers are applied, it will take some considerable time before secondary transition materials can account for a significant proportion of total future demand.

- **Pillar 3: Supply transition materials in accordance with the highest environmental and social standards:** Transition material extraction, refining and downstream processing should adhere to high standards and transparency (no universally agreed standards for transparency currently exist). Fair value capture can be facilitated by channelling investment in sustainable mining and refining in source countries. *GRO24* reveals that only a small proportion of value is currently captured in extracting countries, but the large incoming investment presents invaluable sustainable livelihood opportunities, which should be capitalised on.
- **Groups such as the G7 and G20 can promote a wide range of actions, including:**
 - investing in optimised housing, mobility and nutrition systems;
 - establishing market incentives to make circular economy strategies cost effective;
 - introducing science-based resource use targets for overall material and energy use in housing, mobility and food systems;
 - overcoming barriers to circularity – for example, establishing a taskforce comprised of industry representatives and scientists to agree on the standardisation of battery recycling; and
 - aligning on international mining standards and transparency (eg, through implementing the Sustainable Development Licence to Operate (SDLO), recommended by the IRP).¹
- While we know enough now to take immediate action based on these three pillars, **solutions can be further refined through scientific modelling on their potential impacts.** Funding these efforts should be a priority for government groups such as the G7 and G20.



I SUMMARY

THE WORLD NEEDS TO ACHIEVE THE TWIN GOALS OF THE ENERGY TRANSITION AND RESOURCE DECOUPLING

- **Reaching net-zero GHG emissions is a global priority in the fight against climate change. The energy transition is imperative for all countries** – whether high or low income, producer or consumer. Meanwhile, human wellbeing and economic growth must also be **decoupled from resource use** and its **environmental impacts**. This requires a focus on the **sustainable management of all materials**, including those which are critical to the energy transition. Efforts to **achieve climate targets through the energy transition** should thus be **aligned and consistent with decoupling efforts**.
- The IEA projects that demand for transition materials will increase by approximately **350% by 2030**, but current trends indicate that supply will be unable to keep pace – **shortfalls of key materials, including lithium and copper, are forecast**. Therefore, strategic material management is essential.
- However, progress towards both net zero and decoupling has stalled alarmingly. According to emerging findings from the IRP's forthcoming *GRO24*, **global material use has increased more than threefold since 1970** and has nearly doubled per capita over the same timeframe. Material extraction and processing – including biomass cultivation and harvesting – account for more than **90% of land-related biodiversity loss and water stress, 55% of GHG emissions and 40% of pollution-related health impacts**. All figures have increased since the IRP's last *Global Resources Outlook* was produced in 2019. If current trends continue, global material consumption is projected to rise from approximately **100 billion tons in 2020 to 160 billion tons in 2060**, with the attendant environmental impacts. As significant GHG emissions are driven by material extraction and processing, the continued rise will make net zero increasingly difficult to achieve.
- Material consumption has contributed to human wellbeing gains, but these have been **unevenly distributed**. High-income countries have benefited most from resource extraction and have historically caused the planetary crisis, while emerging and developing economies face the worst impacts.
- To avoid severe environmental impacts, **decoupling** – which breaks the links between unchecked resource use, economic development, human wellbeing and environmental impacts – is vital. In high-income countries, **absolute decoupling** – decreasing material use while maintaining or improving wellbeing outcomes – should be the goal. In low and some middle-income countries, where additional material use is still needed to develop infrastructure and meet people's basic wellbeing needs, the focus should be on **relative decoupling**: sustainably increasing resource use at a slower rate to improve wellbeing (including economic growth)

Countries need to manage potential environmental and social risks and challenges, taking into consideration impacts across the whole transition materials lifecycle.

while minimising environmental impacts and maximising the delivery of essential needs. This is both necessary and just. To avoid risks and capitalise on opportunities, the strategic management of transition materials is crucial.

- In this Co-Chair opinion piece, we define **‘transition materials’** as meeting two criteria:
 - They are materials which are essential to key energy transition technologies (eg, the electrification of mobility needs powerful lithium batteries, while the expansion of electricity grids requires extensive copper cabling); and
 - They are either **projected to see significant growth in demand** or likely to experience **supply-demand** gaps in the next decade or so. In particular, we **focus on materials for which supply at scale is a new challenge**. These include lithium and copper, for which demand is expected to exceed supply by **2030**.
- **Material demand (biomass, metals, non-metallic minerals and fossil fuels) for the energy transition is lower compared to continuing with the fossil fuel-based energy system.** However, **specific transition material needs are high and present complexities which must be managed strategically to avoid jeopardising the energy transition.** These include potential supply-demand gaps, high geographical concentration, the social conditions of global supply chains and location-specific environmental impacts. Countries must address the potential environmental and social risks and challenges, taking into consideration the impacts across the entire transition materials lifecycle.
- New material demand will also yield opportunities, especially for source countries. Large capital investments are likely to flow into mining and refining: according to the ETC, a total **investment of \$1.1-\$1.7 trillion** will be needed for transition material mining, refining and recycling by 2050, with 75% of this required in the next decade. This could **unlock a market opportunity of up to \$10 trillion** over the same period.^a Strategic transition material management can ensure that this capital is used to **reduce environmental and social impacts along the full transition materials value chain**.
- As countries develop their transition materials management strategies, we, the IRP Co-Chairs, suggest that **these should be underpinned by three solution pillars**:
 - **Pillar 1: Mitigate the underlying drivers of demand:** By optimising material and energy-intensive systems – including mobility and housing, where research of IRP has already focused – wellbeing outcomes can be delivered to society using **less energy and fewer, less impactful materials**, thus improving the feasibility of the energy transition. The IRP’s upcoming *GRO24* reveals that optimising key material and energy-intensive systems could reduce **global energy demand by approximately 50% by 2060** (compared to business as usual). Optimising mobility and built environment systems could reduce energy demand by approximately **50% (mobility)** and **30% (buildings)** over the same period; while **overall annual copper demand** for transport applications (cars, trains, bicycles) could be reduced by over **60%**.

^a These figures are largely based on current demand trends in housing and mobility.

- **Pillar 2: Apply all circular economy levers to transition materials and technologies that contain them:** The value and function of each extracted unit of transition materials should be maximised across the whole lifecycle in order to reduce demand for virgin extraction. There is significant potential to establish a reliable secondary supply in the future: currently, **just 1% of the world's lithium is recycled**. The barriers to lithium recycling should thus be overcome. For copper, maximum efficiency grids, grid lifespan extension and recovery and reuse at end of life will likely have the greatest impact. For example, the EU could potentially recover at **least 20% more copper from grids at end of life**. However, **future demand for transition materials will be much greater than it is today**, and it will **take some time before a secondary supply can cover a significant proportion of this demand**. Thus, in the short and medium term, this will not suffice to meet a large proportion of demand.
- **Pillar 3: Supply transition materials in accordance with the highest environmental and social standards:** While Pillars 1 and 2 aim to reduce overall demand for transition materials, their increased extraction and supply will still be necessary. These should be undertaken on the basis of high environmental and social standards.

Among other things, this will involve aligning supply with sustainable development outcomes and fair value capture for source countries and improving global supply resilience through geographical diversification. There are also **abundant opportunities** to be gained in source countries through the fair **channelling of incoming investment in sustainable transition material mining and refining**. The upcoming *GRO24* reveals that only a small proportion of value is currently captured in material extracting countries.

- **To minimise the risks for the energy transition – and allay arguments about its feasibility – the solutions outlined in Pillar 1 are essential.** However, these are largely missing from existing transition materials policies. **Current strategies^b** do suggest some of the solutions outlined in Pillars 2 (circularity) and 3 (sustainable expansion of supply), but this is not enough: key action gaps must still be filled.

Concerted global action could enable comprehensive implementation and align transition materials management with decoupling.

Pillar 1 action recommendations:

- Encourage investment in optimised housing and mobility systems by national governments, multilateral financial institutions (eg, the World Bank) and supranational groups (eg, the G7 and G20).

^b Strategies include the EU's proposed Critical Raw Materials Act and the G7 Five-Point Plan for Critical Minerals Security.

- Give science a clear mandate (eg, from the G20) to develop resource use targets (within a specific timeframe) to reduce overall material and energy demand through efficient housing and mobility systems. This is important in order to decouple energy and resource use from wellbeing and environmental impacts, to ensure that humanity can thrive within a safe operating space. It will also facilitate the energy transition and help to mitigate demand for transition materials. National policymakers should plan for absolute or relative decoupling depending on their level of current resource use and their requirements to meet essential human needs.

Pillar 2 action recommendations:

- Prioritise circular economy measures for transition materials where supply-demand gaps are most likely (ie, lithium and copper).^c It will take some considerable time before secondary supply can meet a significant proportion of future demand for transition materials
- Overcome barriers to lithium battery recycling by standardising recycling and improving economic viability – for example, by establishing a taskforce comprised of industry representatives and scientists to align on a common battery recycling process.

- Maximise function per unit of copper in electricity grids through capacity building for lifespan extension and reuse at end of life.
- Establish a multilateral commitment to sharing research, innovation and best practice on circular economy strategies for transition materials.

Pillar 3 action recommendations:

- Agree on operating standards for mining that are aligned with sustainable development – for example, by implementing the SDLO recommended by the IRP. Extraction, refining and recycling projects which can prove they comply with the SDLO should be able to qualify for climate finance.²
- Ensure mandatory levels of transparency through the disclosure and monitoring of environmental and social risks across the entire transition materials value chain.

While **we know enough now to take immediate action, priorities can be further refined through scientific work.** The immediate direction of travel is clear, but scientific modelling on the effectiveness and regional specificity of different solutions is still nascent and must improve. This would enable precise targeting of the most effective solutions for transition materials. Providing funding for scientific modelling efforts should be a priority for government groups such as the G7 and G20.

^c It will take some considerable time before secondary supply can meet a significant proportion of future demand for transition materials, but circular economy strategies can mitigate the need for virgin transition material extraction.

I INTRODUCTION

THE WORLD MUST ACHIEVE THE ENERGY TRANSITION AND RESOURCE DECOUPLING

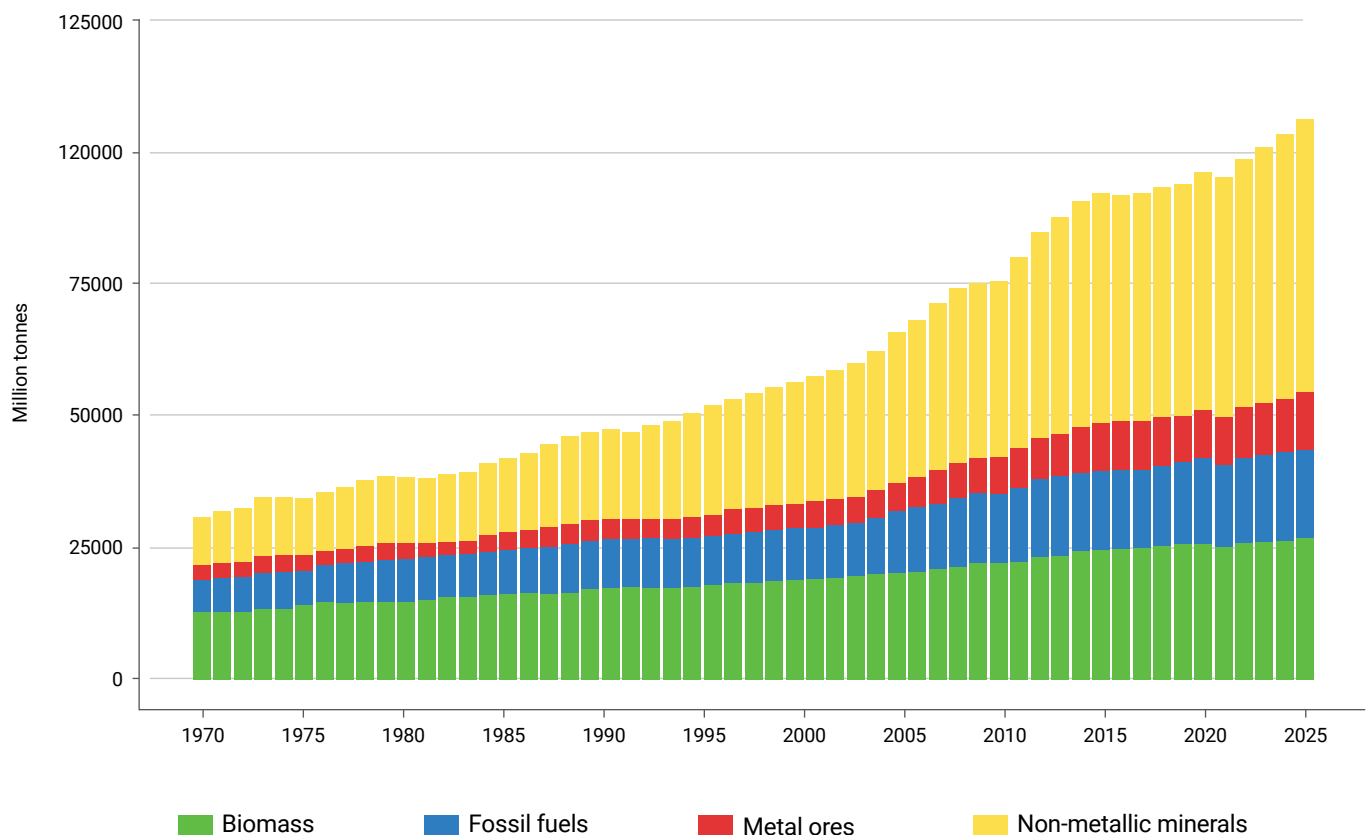
The extraction and processing of material resources (biomass, minerals, metals, fossil fuels) are fuelling all aspects of the triple planetary crisis, accounting for 60% of GHG emissions (including land use change emissions), over 90% of biodiversity impacts (mainly due to biomass cultivation and extraction through agriculture and forestry), and 40% of pollution-related health impacts.^{3,4}

These impacts will likely increase as material consumption continues to grow: global extraction of raw materials has accelerated since 2020 (Figure 1).⁵ Unchecked resource use, largely driven by affluent lifestyles in high-income countries, is driving the triple planetary

crisis;^{6,d} meanwhile, a significant proportion of the world's population still live without their basic human needs being met.⁷

The world still operates with a fossil fuel-based energy system. Currently, approximately 80% of global energy is generated through the combustion of fossil fuels.^{8,9} This energy system is inherently linear, providing another rationale for the energy transition: as well as reducing GHG emissions and other environmental impacts, this presents an opportunity to build circularity into the energy system. After first use, material components can be recycled and reused.¹⁰

^d The IRP's upcoming GRO24 reveals that affluence is the main driver of material use globally.

Figure 1. Global extraction of materials is increasing.^{11, e}

The **impacts and benefits of resource use** are distributed unequally between major resource consumers (high-income countries) and the main resource producers (mainly low and middle-income economies). High-income countries have benefited most and have historically caused the planetary crisis; while emerging and developing economies hold least responsibility but face the worst impacts.

Decoupling – which breaks the links between unchecked resource use, economic development, human wellbeing and environmental impacts – is essential. In high-income countries, absolute decoupling

– decreasing material use while maintaining or improving wellbeing outcomes – should be the goal. In low and some middle-income countries, where additional material use is still needed to develop infrastructure and meet people’s basic wellbeing needs, the focus should be on relative decoupling: sustainably increasing resource use at a slower rate to improve wellbeing (including economic growth), while minimising environmental impacts and maximising the delivery of essential needs. This is both necessary and just: resource use should contribute to decent lives for all.

^e The IRP defines ‘materials’ as fossil fuels, metals, minerals and biomass. Land and water are additional resources studied by the IRP, but are considered materials (*Global Resources Outlook 2019*).

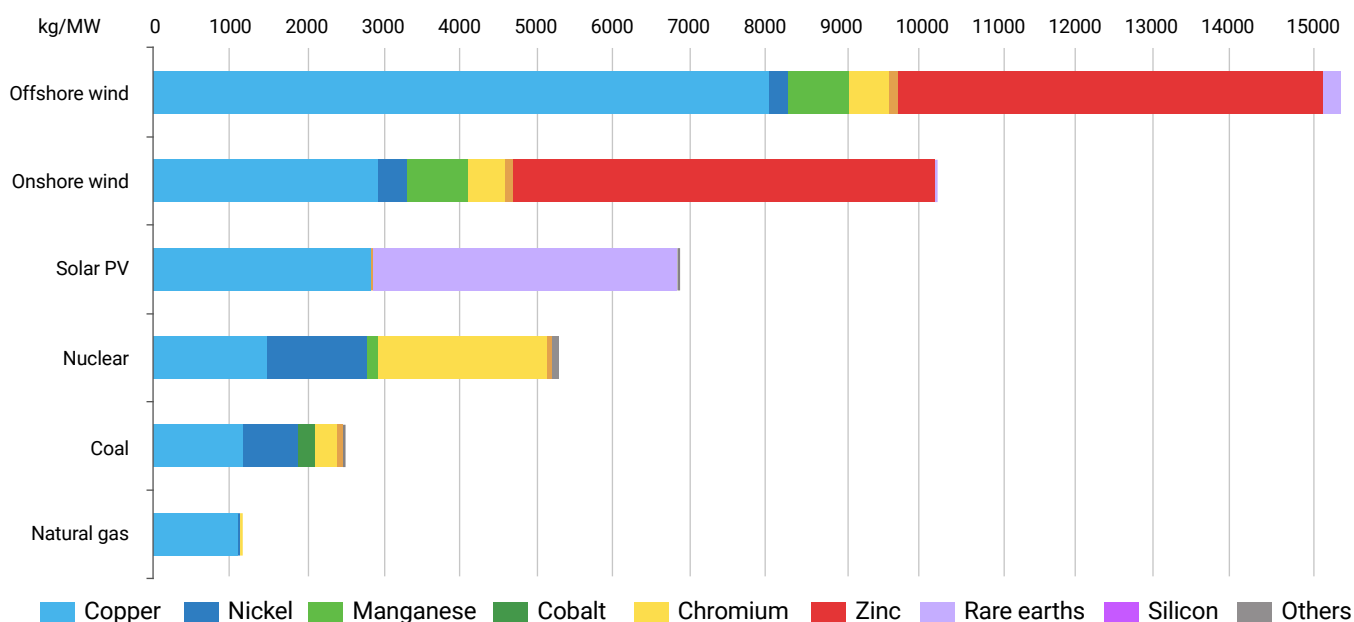
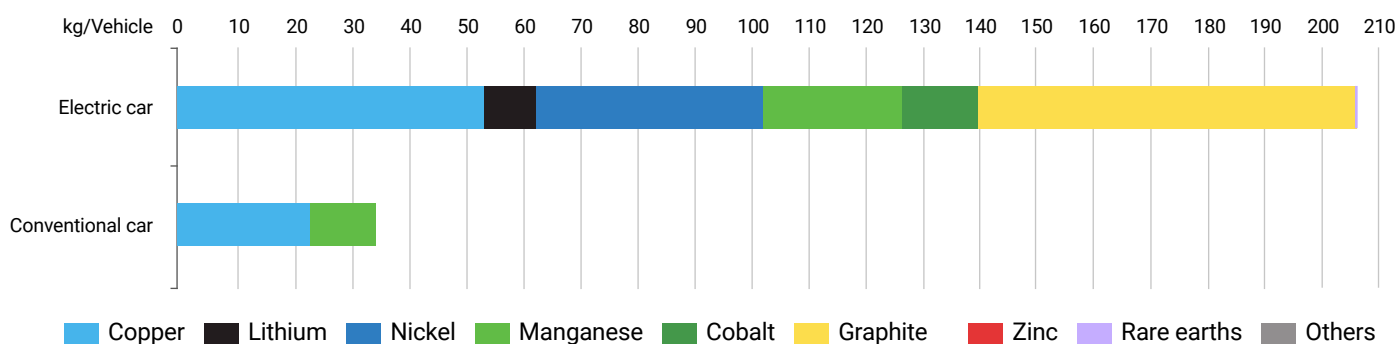
THE ENERGY TRANSITION BRINGS NEW MATERIAL COMPLEXITIES

The **energy transition** is now well underway and will be crucial in combating the triple planetary crisis of climate change, biodiversity loss and pollution.^{f, 12} According to the IEA, there are **substantial new material** needs for clean energy supply (Figure 2).¹³ To reach net zero by 2050, the use of transition materials must increase almost sixfold by 2040.¹⁴ Even meeting today's under-ambitious national climate plans would see the use of transition materials almost double.¹⁵ Technologies that are vital to the energy transition – such as solar photovoltaic (PV) panels and electric vehicles (EVs) – require a higher volume and a more diverse mix of transition materials.

For example, EVs use almost 10 times more transition materials than conventional cars and encompass eight different types of materials, compared to just three for conventional cars.¹⁶ Meanwhile, the supply of mined and refined transition metals is highly geographically concentrated, increasing the risks to value chain resilience.¹⁷

While transition materials will need strategic management, it is important to bear in mind that they are replacing inherently linear and environmentally catastrophic fossil fuels. It is absolutely clear that the shift away from fossil fuels is imperative.

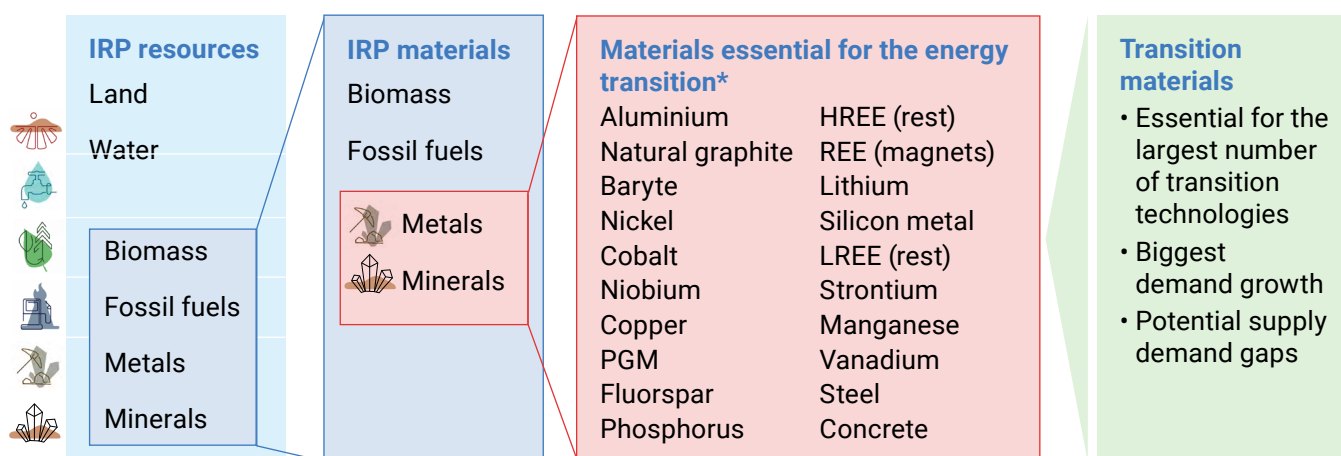
^f When new mining requirements are accounted for, green energy impacts per unit of power generated are much lower than fossil-fuel related impacts.

Figure 2. The energy transition needs more – and more diverse – key minerals¹⁸**Minerals used in clean energy technologies compared to other power generation sources****Minerals requirements of electric and conventional cars**

The **energy transition depends on certain key materials** – both industrial materials used across many sectors (eg, steel, aluminium, copper) and materials essential to energy transition technologies but not widely used in other sectors (eg, lithium).

As shown in Figure 3, the **focus of this opinion piece** is on a subset of materials used in energy transition technologies for which the scale-up of supply is a new challenge: materials which will be in greatest demand over the coming decades or whose supply will likely fall short of demand (based on both current supply and the projected pipeline to 2030).^{19, g}

^g The minerals deemed 'critical' by the EU, Australia, India, the African Development Bank, the US, Japan, Canada and China largely overlap with our selected transition materials.

Figure 3. Transition materials are projected to see high demand growth or to suffer from supply-demand gaps

* Joint Research Centre (JRC) defines 18 metals and minerals as essential for the energy transition as they are crucial to energy transition technologies. These materials are also covered by India's Critical Minerals Strategy. Core minerals for a future African Green Minerals Strategy include 13 minerals – and exclude Baryte, Silicon, Strontium, concrete (as the focus is on raw materials), and Fluorspar. Rare earth elements (REE) are not subdivided into 'heavy' (HREE) and 'light' (LREE) in this classification).

Material	Technology	Demand growth until 2050 (% 2021 demand)
Graphite		1200%
Lithium*		750%
Niobium*		375%
Silicon metals		340%
Cobalt		185%
Nickel*		170%
Copper*		150%
Aluminium		50%

Technology	Li-ion batteries	Fuel cells	Electrolysers	Wind turbines	Solar PVs	Heat pumps	H ₂ -direct reduction	Traction motors

* Demand is likely to outstrip supply before 2030, based on supply from existing mines and the current pipeline of mines in development.

Sources: For demand growth: ETC (2023). Material and Resource Requirements for the Energy Transition
For Transition Technologies: JRC (2023). Supply Chain Analysis and Material Demand Forecast

While other materials – including steel and cement – are also needed for the energy transition, their supply at the necessary scale presents no challenges. The projected demand growth for steel and cement is considerably lower than that for transition materials and no supply-demand gaps are anticipated.^{20, h}

However, significant challenges are associated with decarbonising the production of steel and cement.^{i, 21, 22} The decarbonisation of both sectors is a high priority, given that each accounts for 7% of global emissions respectively.²³

^h The World Economic Forum projects that demand for steel will grow by 30% and for cement by 45% by 2050.

ⁱ Steel and cement decarbonisation pathways are examined in detail by the Mission Possible Partnership.

TRANSITION MATERIALS NEED STRATEGIC MANAGEMENT

The new material needs of the energy transition present complexities that must be managed strategically. They include potential supply-demand gaps, high geographical concentration (making global supply vulnerable to local shocks), the social conditions of supply and location-specific environmental impacts. The potential environmental risks and challenges related to the increased use of transition materials must be addressed across their entire lifecycle. Therefore, efforts to reach net-zero GHG emissions and to achieve the energy transition must be aligned and consistent with decoupling efforts. For example, efforts to decarbonise mobility should also seek to reduce overall material use; a shift to green public transport would contribute to both goals. This would not only help to minimise the environmental impacts of the transition materials utilised in this regard, but also accelerate and facilitate the energy transition. Countries are in the process of working out how best to manage these new demands and risks. Patterns of value capture could also be updated to bring more benefit to source countries.

Recent reports by bodies such as the ETC and the IEA provide important quantitative insights into transition materials, primarily focused on supply-side challenges. However, comprehensive transition materials strategies are still missing and require the attention of global leaders.

A systemic approach will be needed if transition materials strategies are to be truly effective. However, two opposing schools of thought are currently hindering such an approach. Some argue that the complexities presented by transition materials threaten the feasibility of the energy transition; while others contend that the energy transition can be achieved through narrow, supply-side focused transition material strategies, with a limited view of the potential of demand-side solutions.

Other concerns in this regard relate to shaky global resilience and unfairly distributed value capture.²⁴

This **opinion piece makes the case for an honest debate and committed policies** to credibly disprove the transition sceptics while also responding to legitimate fears by proposing necessary actions. We strongly emphasise that the energy transition is both necessary and possible, and that its material requirements can be met if the right policies and incentives are in place (as recent reports confirm).^{25, 26} We also stress that both material requirements and energy needs can be controlled and limited through an in-depth 'provisioning systems' transformation (see Pillar 1 and Box 2).

Countries are in the process of working out how best to manage these new demands and risks. Patterns of value capture could also be updated to bring more benefit to source countries.

We should embrace fundamental changes in how we consume energy and resources in order to build the required level of resilience and minimise risks both to the environment and to a timely and comprehensive energy transition. Most existing transition material strategies still overlook this perspective. At the same time, we should seize the opportunities that heightened demand for transition materials will bring for source countries, including the need for global investment and trade to enable fair value capture, which requires enhanced transparency and governance.²⁷

We strongly argue that **further scientific work is needed in this regard** – in particular, modelling to explore the potential impacts of different solutions. That said, the current and emerging science is already sufficient to start drawing up comprehensive, systemic transition material strategies.

In addition to existing reports that highlight the abundant potential of circular economy strategies for transition materials management – such as the ETC’s *Material and Resource Requirements for the Energy Transition* – upcoming work by the IRP, and especially its flagship *GRO24*, reveals the extent to which ambitious policies for resource efficiency, climate change and food systems can improve the resource and energy efficiency of the world’s housing, mobility and other resource-intensive systems. Although *GRO24* does not explicitly focus on transition materials, overall demand for energy and materials will inevitably have implications in this regard. For example, increased material demand for EVs will result in heightened demand for the transition materials used in their batteries; while increased demand for steel in vehicles or buildings will result in heightened demand for the transition materials used in decarbonised steel production. *GRO24*’s approach of modelling

human needs delivery shows how we can not only mitigate the underlying drivers of demand growth for transition materials, but also improve their utility for people, enabling us all to move better, live better and eat better in a safer, healthier, fairer world.

The preliminary **modelling data from *GRO24*** reveals abundant potential to reduce the material intensity of urban environments and mobility, which would also reduce the underlying drivers of transition material use while improving human needs delivery and enhancing wellbeing.

Moreover, the IRP’s upcoming report on **financing in the extractive sector** will build on previous seminal works on sustainable mining, including the 2020 report on *Mineral Resource Governance in the 21st Century*. The latest scientific assessments will reveal the potential for improved transparency and increased public and private investment to capture value from extraction and refining, especially of transition materials.²⁸

In this opinion piece, we suggest **three solution pillars** that should underpin national transition materials strategies and suggest global governance improvements to facilitate their adoption and implementation.



RISKS MUST BE ADDRESSED AND OPPORTUNITIES REALISED

RISKS RELATING TO ENVIRONMENTAL AND SOCIAL IMPACTS, SUPPLY-DEMAND GAPS AND GEOGRAPHICAL CONCENTRATION MUST BE MANAGED, WHICH ALSO PRESENTS A MAJOR OPPORTUNITY FOR SUSTAINABLE DEVELOPMENT.

Environmental and social impacts

The scale-up of supply of transition materials will likely generate new environmental and social impacts. It is essential to consider all potential risks across the whole value chain and throughout the entire lifecycle of materials.²⁹ The impact of transition materials extraction is vastly preferable to continued fossil fuel use and less environmentally harmful than other economic activities, including agriculture and forestry.^{30, 31} The climate, pollution and health benefits of transitioning away from fossil fuels are clear.³² Analysis of the biodiversity impact of mining for energy generation from different sources reveals that the impact of fossil fuel mining is approximately seven times greater than that of mining for renewables per unit of energy generated.³³

However, the potential climate, biodiversity and health impacts along the whole value chain should not be underestimated. They can be devastating, including for ecosystems of global significance and the people who live there.³⁴ For example, lithium and copper extraction are co-located in areas that suffer from severe water stress³⁵ and have high water requirements, which further exacerbate this stress. Droughts in major producing regions are becoming more common: severe events

have impacted operations in Chile, Australia, Zambia and other extracting countries.³⁶ Moreover, the expanded supply of transition materials must not come at the expense of people and the planet; and safeguards for Indigenous Peoples and local communities should not be compromised.

Certain transition materials are also co-located in globally significant ecosystems with abundant biodiversity, such as the Amazon basin (Box 1), Indonesia and the Democratic Republic of Congo (DRC).³⁷ Expanded extraction in these areas needs careful planning to avoid the worst biodiversity-related impacts. There is also considerable concern about the potential impact of future deep-sea mining for transition materials: highly endemic biodiversity is at risk of extinction, with grave implications for ecosystem stability and connectivity, ecosystem service delivery and the loss of potential biodiscoveries and other future solutions for humanity from marine genetic biodiversity.^{38, 39} The Convention on Biological Diversity advises countries to fully understand and seek to mitigate the marine biodiversity risks presented by deep-sea mining. Some jurisdictions, including the EU, advocate for a prohibition on deep-sea mining⁴⁰ until the scientific gaps have been filled.^{41, 42}

Analysis of the biodiversity impact of mining for energy generation from different sources reveals that the impact of fossil fuel mining is approximately seven times greater than that of mining for renewables per unit of energy generated.

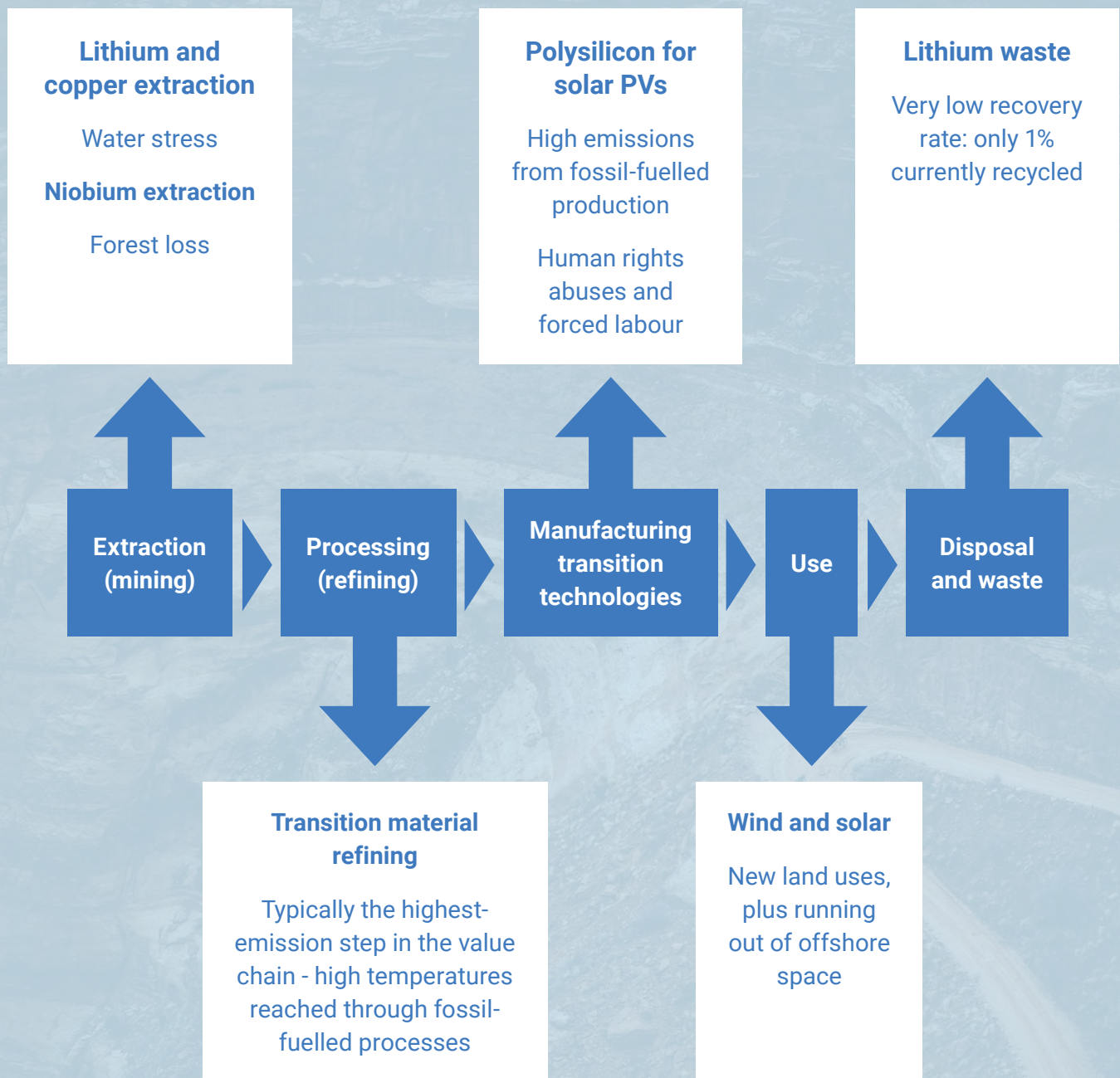
Moving downstream in the value chain, refining is often the step with the greatest environmental impact due to the high temperatures involved (often above 800°C), which are frequently generated by coal combustion.⁴³ After refining, transition materials are used in the development of transition technologies: the worst impacts at this stage concern not only GHG emissions, but also human rights. For example, high emissions and human rights abuses including forced labour must be addressed in relation to the manufacture of solar PV panels.⁴⁴

The use of transition materials for energy generation has a far lower impact than the corresponding use of fossil fuels. However, land use considerations must be taken into account, in particular for solar PV panels:⁴⁵ given the multiple competing pressures on land – including food production, urbanisation and space to meet ecological goals – planning for solar PV panels may prove challenging.⁴⁶

Potential solutions must also consider waste management. Waste from mining should be reduced and could also be recovered more effectively to extract more materials. End-of-life transition materials could make a significant contribution to the future secondary supply (thus reducing the need for virgin extraction), but a large proportion of transition materials is currently lost as waste. For example, just 1% of lithium is recycled due to barriers including diverse battery chemistries, each of which requires its own recycling process; and economic viability – it is currently cheaper to produce new lithium-ion batteries than to recycle them at end of life.^{47, 48}

Mitigating the main drivers of demand for transition materials through the optimisation of resource-intensive systems would help to reduce their impact at all phases of the lifecycle. This would maximise the social and environmental co-benefits and facilitate sustainable materials management – including the management of transition materials.

Figure 4. Illustrative transition materials-related impacts along the value chain

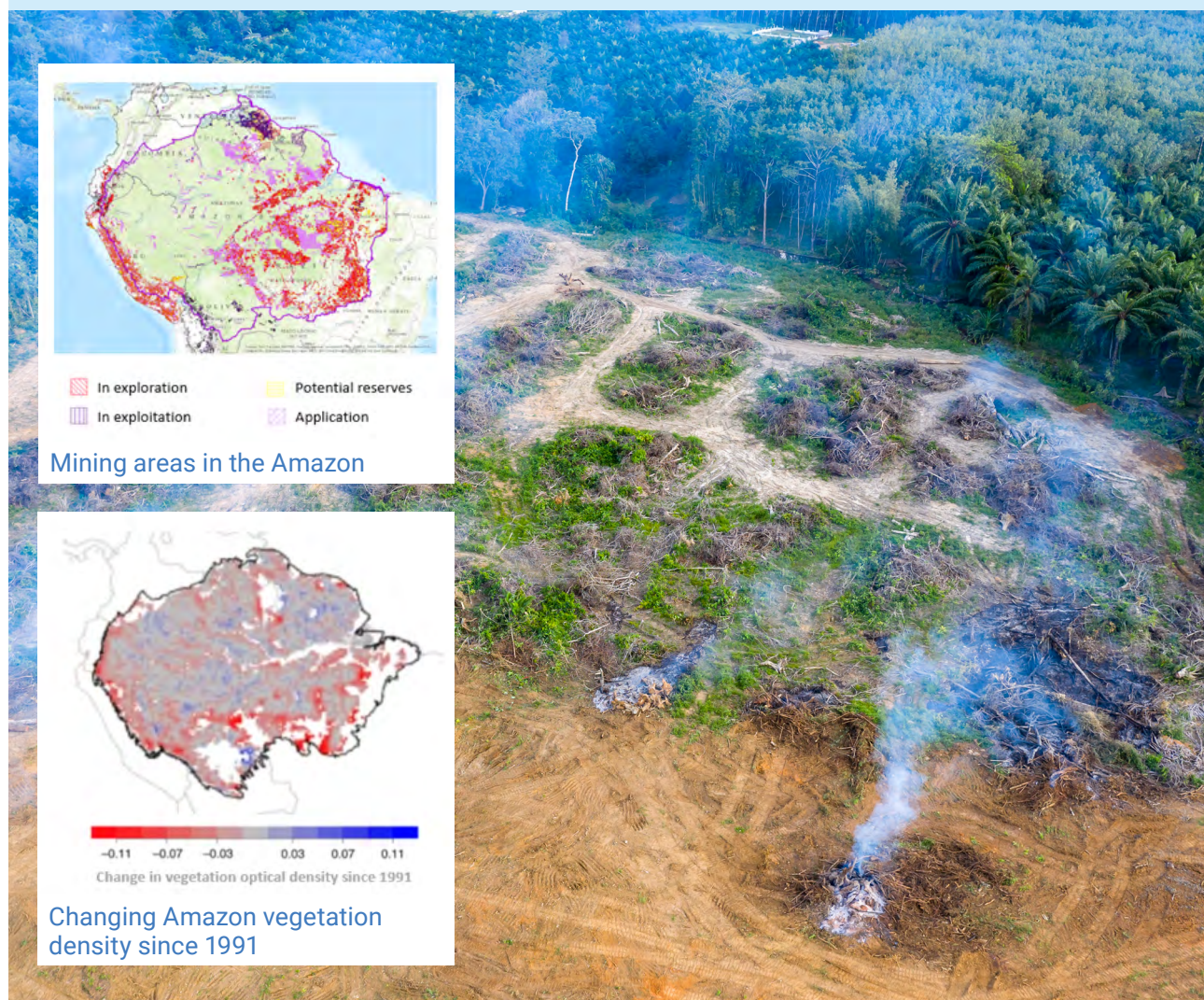


Box 1: Transition materials in the Amazon

The Amazon region is exceedingly rich in transition materials, due to its vast geography and favourable geology. For example, Brazil is home to 94% of the world's niobium, which strengthens steel and is used in the production of electrolyzers and wind turbines;⁴⁹ 22% of the world's graphite; and 16% of all known rare-earth metal reserves (17 scarce elements which are utilised in clean energy technologies), which are primarily located beneath the Amazon basin.^{50, 51} Much of Brazil's critical material wealth has yet to be mapped.⁵² Mining areas – especially those under exploration or application (ie, in which companies have already applied to commence mining operations) – overlap with areas in which the forest has already lost resilience (Figure 5).^{53, 54}

The potential risks to this unique ecosystem must be managed strategically. In August 2023, Brazil hosted the Amazon Summit, which culminated in a call from rainforest nations for financing for rainforest protection from high-income countries.⁵⁵ This joint statement called for strengthened regional and international cooperation to end illegal mining in the area, as well as greater consideration for the safety of forest peoples in mining project development.⁵⁶

Figure 5. Mining areas overlap with areas where forest has already lost resilience.^{57, 58}



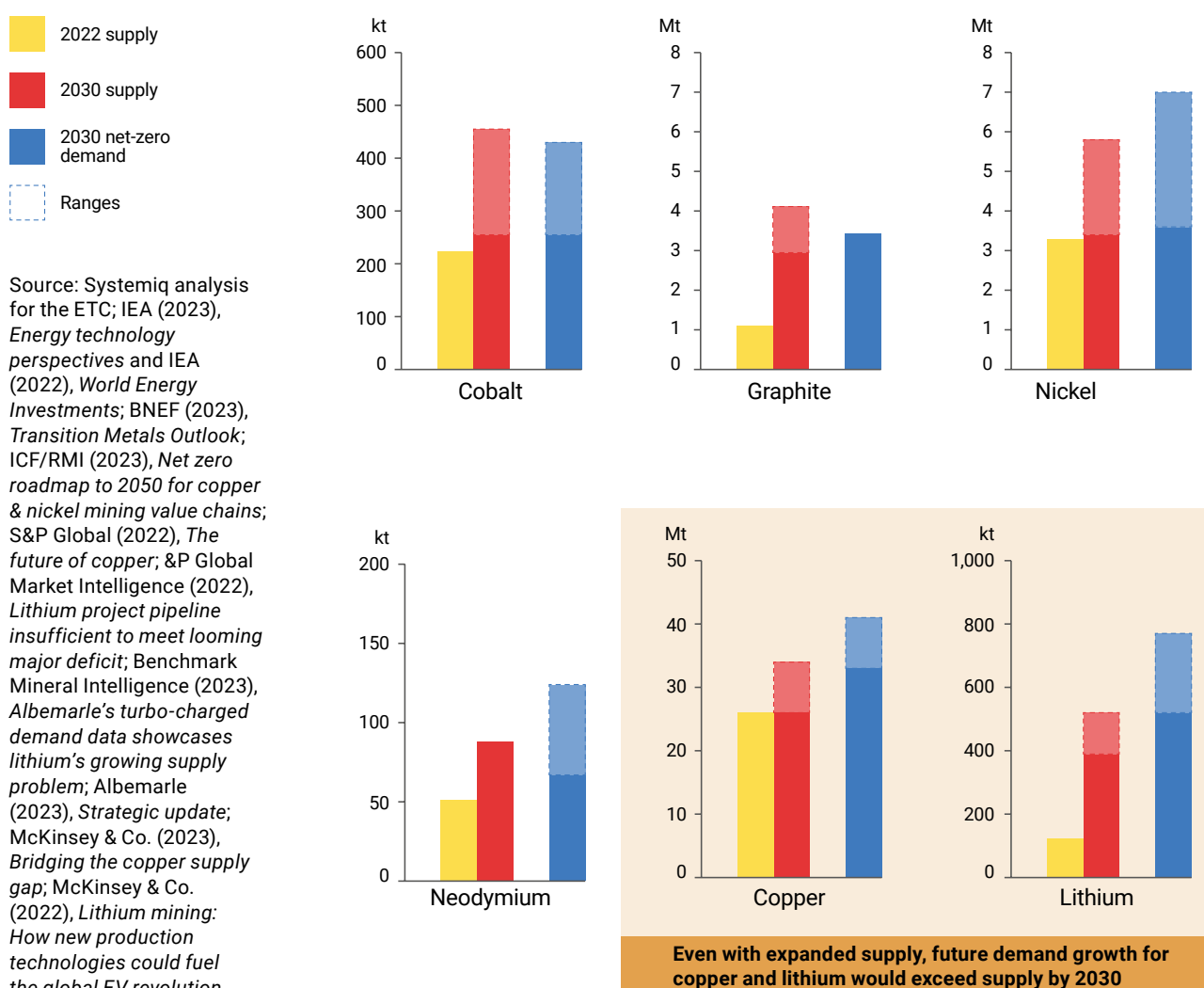
The value generated by transition materials is unequally shared and is primarily captured by the countries that undertake refining and processing activities, rather than the source countries.⁵⁹ The issue of local value capture is gaining attention and countries are increasingly seeking to process mining products domestically, exporting the more valuable refined products rather than raw materials and taxing them efficiently.⁶⁰

Supply-demand gaps and supply chain resilience

Without demand mitigation efforts, supply-

demand gaps are likely for all transition materials, especially copper and lithium. Industry analysis suggests that existing and planned supply pipelines may not result in sufficient copper and lithium to meet projected demand by 2030.^j The usual timeframe from exploration to online supply can be over 10 years, meaning that even if significant new lithium and copper were added to the supply pipeline now, it is unlikely that they would be available before supply-demand gaps emerged.⁶¹ Ensuring their rapid availability would also require considerable additional investment.⁶²

Figure 6. Demand and supply forecasts for key transition materials, showing supply-demand gaps^k
(Adapted from ETC) (2023)⁶³



^j Most current projections do not account for the mitigation of underlying demand drivers by optimising the most material and energy-intensive systems, as highlighted in Pillar 1 and our proposed modelling framework (Figure 12).

^k Industry practitioner analysis.

At present, the extraction and refining of key transition materials are relatively geographically concentrated, increasing the risk of regional events affecting overall supply – which in turn could impact supply chain

resilience. Over 80% of the world’s lithium refining takes place in just two countries, while 80% of rare earth mineral refining takes place in a single country.⁶⁴

Figure 7. Locations of copper production worldwide (30% Chile; 10% Peru; 8% China; 8% DRC)⁶⁵

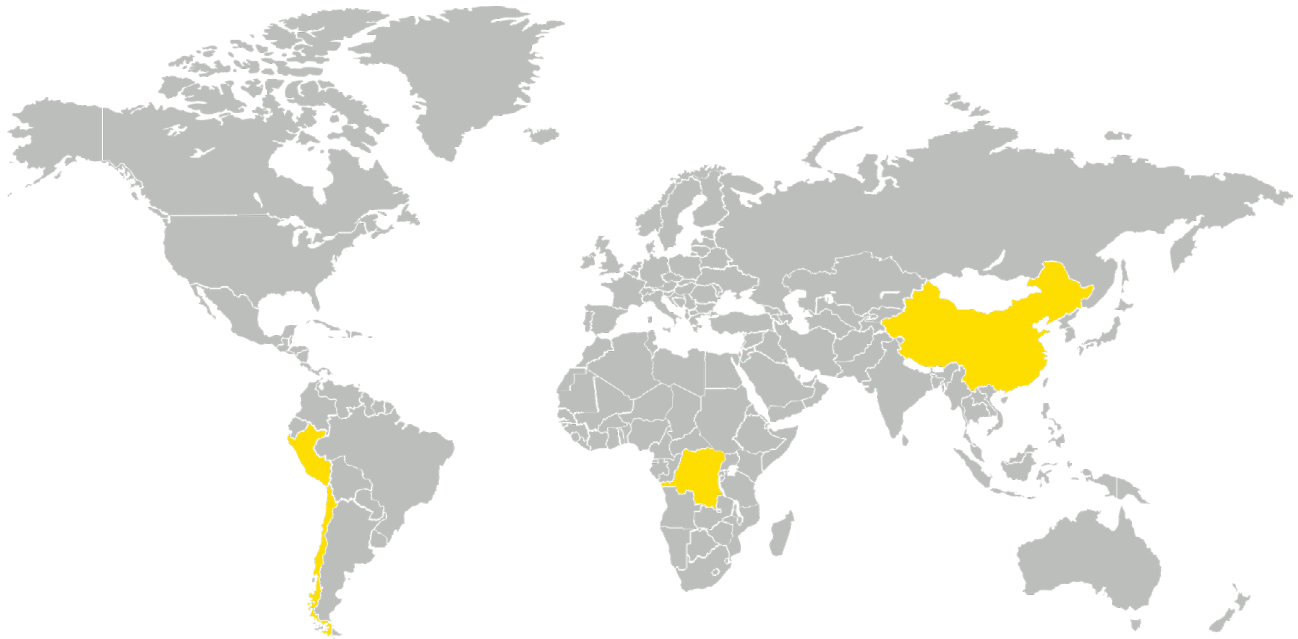
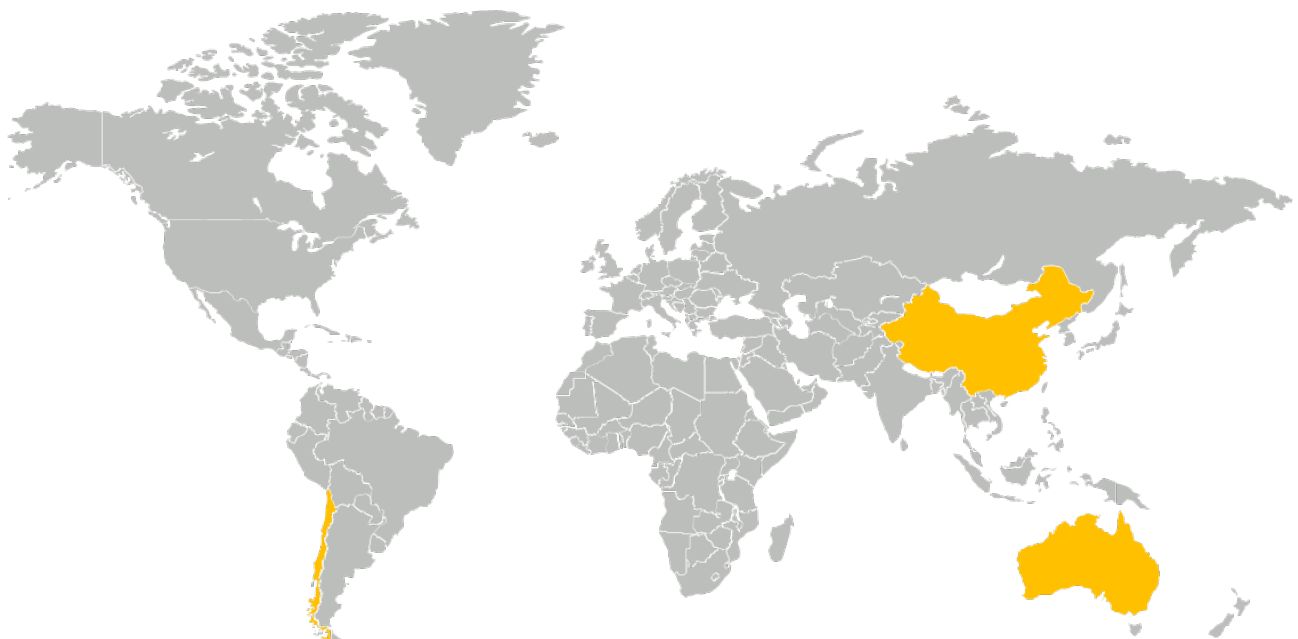


Figure 8. Locations of lithium production (46% Australia; 24% Chile; 16% China)⁶⁶



Therefore, strategies are needed to address the environmental and social impacts along the value chain, avoiding supply-demand gaps, mitigating the vulnerability of highly concentrated supply to local shocks and ensuring a just value distribution. To this end, the energy system should be decoupled from material dependence as far as possible.

Major opportunities for a just value distribution

This is also the right time to **capitalise on the opportunities presented by transition materials**. In the coming years, significant amounts of capital investment will flow into the mining, refining and recycling of transition materials. The ETC projects that a total investment of \$1.1-\$1.7 trillion will be

needed for these activities by 2050, with 75% of this required in the next decade (these figures are largely based on the continuation of current trends in housing and mobility).⁶⁷ This investment could unlock a market opportunity of up to \$10 trillion over the same period.⁶⁸ Policymakers should ensure that the capital is channelled towards reducing the environmental and social impacts across the entire transition materials value chain. With the right governance arrangements in place, the extraction and recycling of transition materials can support sustainable development, capturing value for source countries and regions.⁶⁹ Opportunities for redistribution through resource efficiency and circular economy measures should also be considered.



WELLBEING CAN BE MAXIMISED, RISKS MITIGATED AND THE ENERGY TRANSITION FACILITATED THROUGH THREE SOLUTION PILLARS FOR STRATEGIC TRANSITIONAL MATERIALS MANAGEMENT

The need to achieve decoupling and the energy transition simultaneously is clear from the existing and emerging science, and has already been advocated in some important political documents.^l Transition material governance must likewise embrace both objectives.

We propose that by operationalising three spheres of policy action, it will be possible to reduce impacts and risks, strengthen energy system resilience and yield multiple benefits for society.⁷⁰ These three 'solution pillars' are as follows:

Pillar 1: Mitigate the underlying drivers of demand by optimising material and energy-intensive systems.

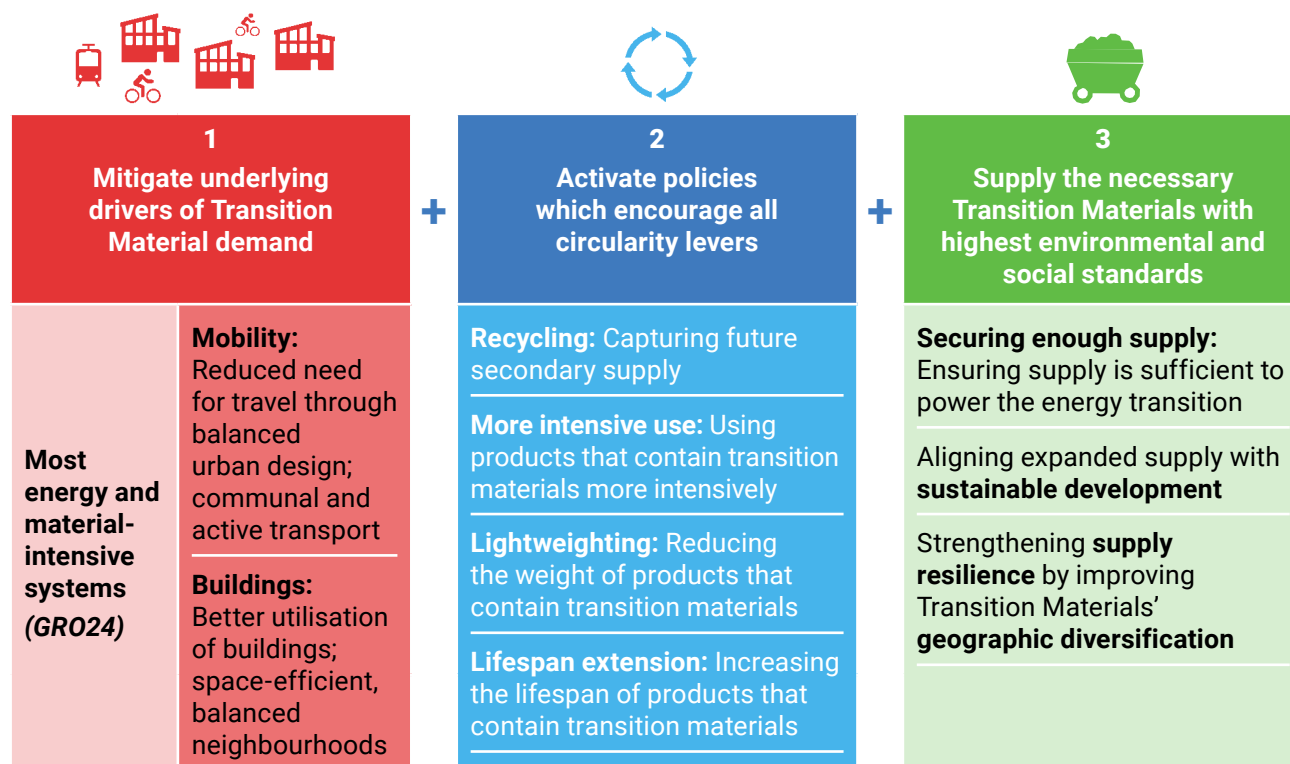
Pillar 2: Apply all circular economy levers to

transition materials and technologies that contain them.

Pillar 3: Supply transition materials in accordance with the highest environmental and social standards.

While each pillar is important, this opinion piece focuses on the most commonly overlooked solutions: those in Pillar 1. Although much remains to be done to fully operationalise Pillars 2 and 3, these solutions have already been captured to a certain extent by existing policy documents and recommendations. However, Pillar 1 has thus far been omitted from existing transition material strategies and this gap must be addressed.

Figure 9. Three solution pillars for transition materials resilience and key focus areas to incorporate in future transition materials management strategies, with potential outcomes^m



^l The European Green Deal, for example, includes the target of the geographical diversification of transition materials, no net emissions of greenhouse gases in 2050, and where economic growth is decoupled from resource use.

^m Policies reflect insights from the IRP's forthcoming report on financing in the extractive sector and GRO24, and IRP (2020).

PILLAR 1: MITIGATE THE UNDERLYING DRIVERS OF DEMAND BY OPTIMISING MATERIAL AND ENERGY-INTENSIVE SYSTEMS

Pillar 1 aims to reduce demand both for energy overall and for energy-intensive materials (eg, using less steel and cement to meet housing and mobility needs), which in turn will reduce demand for the use of transition materials in decarbonised material production. Policymakers should focus on Pillar 1 solutions both to reap these multiple

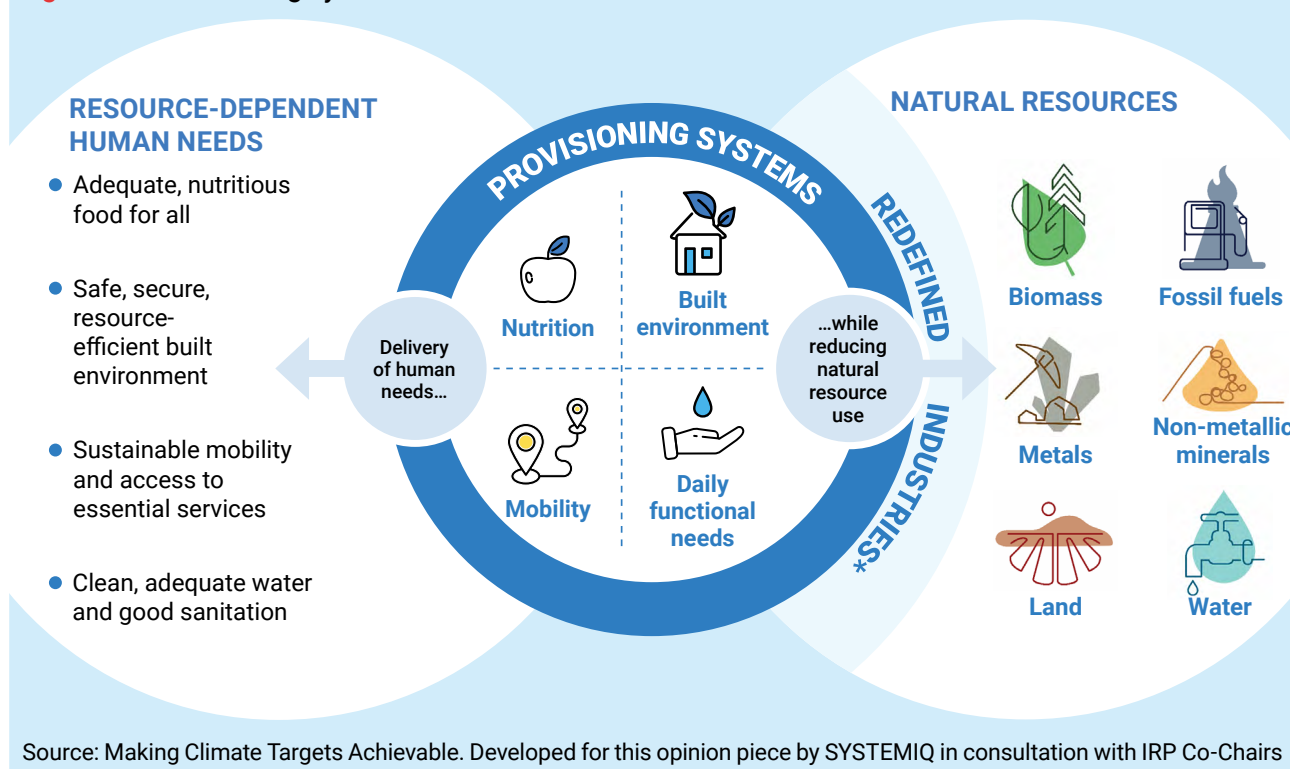
co-benefits and to accelerate and facilitate the energy transition. To avoid unintended consequences, solutions should be designed with overall wellbeing as the central aim and appropriate metrics for the wellbeing performance of energy and material-intensive systems should be developed for this purpose.

Box 2: The benefits of a provisioning systems approach

Decoupling human wellbeing from resource use will require solutions for ‘provisioning systems’: the resource-intensive systems that deliver human needs. Optimising these systems to meet societal needs with minimal resource input will improve overall wellbeing while reducing materials demand and mitigating the environmental impact.^{71, 72}

Holistic solutions for provisioning systems afford greater opportunities and increased societal co-benefits than specific supply-side solutions applied in individual sectors. For example, while a focus on resource efficiency in the automotive sector could produce leaner and more efficient vehicles, it would miss opportunities linked to new ownership models that increase vehicle utilisation, a shift to other transport modes or reduced need for travel in the first place through more compact city design or increased remote working. The abundant potential for absolute resource reduction would thus be overlooked.⁷³

Figure 10. Provisioning systems use natural resources to deliver human needs⁷⁴





In this opinion piece, we focus in particular on shifts in mobility and the built environment. Previous IRP research and the upcoming *GRO24* demonstrate that these are among the most material and energy-intensive provisioning systems.^{75,76} The built environment system in particular is a key determinant of energy demand, second only to overall GDP.⁷⁷ Optimising the delivery of these needs can reduce overall energy use and thus help to mitigate future demand for transition materials.

Governments and investors can act now to ensure that provisioning systems can deliver human needs while reducing overall energy and material demand. There is no need to await the expanded extraction of transition materials or the availability of a secondary supply.⁷⁸ Optimising the resource efficiency of material and energy-intensive systems (in particular buildings and mobility) can

accelerate and de-risk the energy transition beyond demand for transition materials themselves – for example, by reducing the need for biofuels or not-yet-scaled carbon capture and storage technologies, and addressing the broader environmental challenges associated with high material and energy needs.

The IRP's next flagship report, *GRO24*, will explore the impact of using fewer resources and less energy in the provisioning systems on which we rely to meet our mobility, shelter, nutrition and functional (eg, communication, sanitation) needs. This operationalises the IRP's concept of decoupling: breaking the links between unchecked resource use and human wellbeing.⁷⁹ The implementation of ambitious systemic resource efficiency measures could reduce global energy demand by approximately 50% by 2060 (compared to business as usual).⁸⁰

PRELIMINARY FINDINGS FROM THE *GRO24* MODELLING

The mobility and housing systems are both direct and indirect drivers of transition material demand. First, they are energy intensive and thus require the use of transition materials – for example, for the production of EV batteries and the generation of electricity. Second, they necessitate the direct use of transition materials, such as copper in vehicle shells and construction materials (eg, roofing and building cladding).⁸¹ Third, they use other materials – such as steel and cement – which are highly energy intensive to produce at present and whose decarbonisation will rely on transition materials. More than 50% of global steel production is used in building construction, while over 15% is used in the auto sector.⁸² Thus, reducing material and energy intensity in the mobility and housing systems could help curb overall demand for transition materials demand while increasing the ease and speed of the energy transition.

In the mobility system, increased road and air transport is a major driver of emissions. Activating Pillar 1 solutions such as modal shifts to public transport (combined with Pillar 2 circularity solutions) could reduce overall annual copper demand for transport applications (eg, cars, trains, bicycles) by 60%⁸³ and mobility system energy demand by 50% by 2060 (compared to business as usual).⁸⁴

This shift would be achieved by transforming the design of the mobility system itself – for example, by reducing the need for travel through the promotion of remote working and compact urban design; and by designing mobility infrastructure to increase the use of public and active transport and minimise the use of individual vehicles.⁸⁵

Resource efficiency measures – including vehicle lightweighting, more intensive vehicle use and extended vehicle lifespans – can also help to reduce material and energy demand. (Further circular economy and resource efficiency solutions are discussed in Pillar 2.)ⁿ

In the housing system, modelling for the forthcoming *GRO24* reveals that the systemic optimisation of service delivery (combined with Pillar 2 circular economy and resource efficiency solutions for buildings) could reduce overall energy demand by approximately 30% by 2060, which would relieve the pressure to source transition materials. It could also reduce the total material stock in the built environment by 25% by 2060 – mostly in relation to steel and concrete, but also encompassing other metals such as copper and aluminium.⁸⁶

ⁿ Detailed assumptions will be provided in *GRO24*.

Smarter sharing of equipment, appliances and machinery in more interactive neighbourhoods would further reduce energy and materials demand.

These shifts would be achieved through better utilisation of empty homes and other underutilised spaces, and more community-focused living that reduces the need for new housing. Combined with balanced neighbourhood designs, in which all essential services are located within walking or cycling distance, this would reduce the growth of built infrastructure.⁸⁷ In addition, smarter sharing of equipment, appliances and machinery in more interactive neighbourhoods would further reduce energy and materials demand.

Along with energy system innovations such as lightweight renewable energy infrastructure with longer lifespans, these changes to the mobility and housing systems

could result in substantial reductions in overall energy demand. According to the forthcoming GRO24, the combined implementation of Pillar 1 and 2 solutions could cut overall final energy demand by around 50% by 2060.⁸⁷

The optimised delivery of human needs through high-performing provisioning systems would yield not only environmental benefits, such as improved air quality, but also wider societal co-benefits – especially in urban environments – including more space for nature and a heightened sense of community. Cities that make efforts to optimise provisioning systems also enjoy high levels of citizen satisfaction and reduced inequality.⁸⁸

⁸⁷ Detailed assumptions will be provided in GRO24.

Figure 11. High-performing built environment systems bring multiple societal co-benefits⁸⁹

A high-performing housing/built environment system featuring **circular buildings within a balanced, compact neighbourhoods with concentrated service delivery...**

...has maximum benefits for TM resilience...

Material use

Energy use

TM use

Less energy and materials needed for building construction, building heating and cooling, street construction and vehicles

Lower overall TM demand for green energy provision and material production

...as well as for people, business and nature

Urban innovation

Well-designed, dense neighbourhoods boost innovation and productivity

Housing crisis

Balanced space efficiency enables higher-quality space for everyone

Land use + nature access

Less land sealing for housing and sprawled infrastructure + shorter distance to nature for everyone

Speed of built environment decarbonisation

Low-tech solutions implementable today can reduce emissions, especially from hard-to-decarbonise materials like cement, faster than decarbonisation in production

Source: Systemiq (2022), Efficient and balanced space use: shaping vibrant neighbourhoods and boosting climate progress in Europe

TM = Transition Materials

There are also economic opportunities in the form of job creation to be gained by curbing demand growth through Pillar 1 solutions such as shared mobility services, circular building materials and the retrofitting of buildings.

Powering the energy transition will require a significant increase in demand for transition materials. Overall materials demand for the energy transition, both now and in future, is very low compared to existing resource consumption.⁹⁰ Nevertheless, if we are to meet existing environmental targets and avoid further transgression of planetary boundaries,

resource use will need to fall in high-income countries and increase at a slower rate in low and middle-income countries. Therefore, increased use of transition materials for the energy transition will need to be managed within the context of absolute and relative decoupling. Strategic transition materials management will benefit all parties: source countries likely have more to gain from channelling investment towards high-quality transition material extraction than from maximising the number of lower-value capture mines (with their associated negative environmental and social impacts).

PILLAR 2: APPLY ALL CIRCULAR ECONOMY LEVERS TO TRANSITION MATERIALS AND TECHNOLOGIES THAT CONTAIN THEM

While the focus of this opinion piece is on Pillar 1 solutions, it is also helpful to understand the essential role that Pillar 2 and 3 solutions will play in strategic transition materials management. Future demand for transition materials will be much greater than it is today, but it will take some time before a secondary supply of such materials can cover a significant proportion of this demand, even where all possible options to maximise their availability are utilised to the fullest.

Maximising the availability and use of secondary transition materials will reduce demand for virgin extraction in the long term.⁹¹ Some circular economy levers have been highlighted in existing transition materials strategies, including the proposed EU Critical Raw Materials Act and the G7's Five-Point Plan on Critical Minerals Security.⁹² Policymakers have advocated Pillar 2 policies such as increasing battery recycling and extending the lifespans of electricity networks.^{93, 94} The G7's Five-Point Plan for Critical Minerals

Security and the G7 Climate, Energy and Environment Ministers' Communiqué stress the need for increased recycling of transition materials.⁹⁵ The communiqué also commits to increasing 'sustainable and efficient recovery and recycling of critical minerals and raw materials'.⁹⁶ The proposed EU Critical Raw Materials Act tasks member states with developing national programmes that include measures to increase reuse of products and to develop technologies that promote material efficiency and substitution.⁹⁷ The G7's Berlin Roadmap also commits countries to accelerating progress on these high-impact circular economy strategies. While this is encouraging, other key opportunities are missing:⁹⁸ impactful solutions such as lightweighting, downsizing, lifetime extension and restoration remain overlooked.⁹⁹

By using all possible circular economy levers today, demand for primary transition materials can be reduced in the long term – and especially beyond 2030¹⁰⁰ (see Box 3).

Box 3: Pillar 2 solutions for transition technologies

EVs and energy storage (~50% of transition material demand by 2050)^p

Increased recycling: Battery recycling can reduce demand for primary cobalt, lithium, nickel and copper by around 10% by 2040, according to the IEA.¹⁰¹ Today, a huge proportion of potential future secondary supply is lost to waste – for example, just 1% of lithium is recycled.¹⁰² The barriers to lithium recycling include diverse battery chemistries, each of which requires its own recycling process; and economic viability – it is currently cheaper to produce new lithium-ion batteries than to recycle them at end of life.^{103, 104, q} As initial steps to overcome these barriers, governments should promote battery design for recycling and standardised battery chemistries based on the best available science.¹⁰⁵ Pricing primary raw materials to reflect their environmental impact would also help to improve the economic viability of battery recycling.¹⁰⁶ Industry experts estimate that by 2040/50, 80%/90% of EV batteries should be collected for reuse (eg, promising experiments are being conducted to repurpose EV batteries for community energy storage)¹⁰⁷ and recycling at end of life.

More intensive use:^r While replacing all traditional vehicles with EVs would reduce emissions, it would also result in a significant increase in battery manufacturing.¹⁰⁸ Shared mobility models could reduce the size of the overall vehicle fleet: for example, a free-float car-sharing model could use up to ~54% fewer cars to provide the same utility.¹⁰⁹

Increased energy efficiency and lightweighting: Lightweight EVs can be powered by batteries that use less resource-intensive chemistries, potentially reducing transition material demand by up to 20%.¹¹⁰ According to modelling for the IRP's upcoming *GR024*, car envelopes could be up to 18% lighter by 2060 with the right targets and incentives in place.¹¹¹

Substitution: Sodium is abundantly available and its isolation is a lower-impact process, making sodium-ion batteries a promising alternative to lithium-ion batteries. It is forecast that by 2035, these will account for 3% of EV battery demand and 30% of battery demand for two and three-wheeled vehicles.¹¹²

Electricity networks (~30% of transition material demand by 2050)^s

More intensive use: Smart grids are cohesive platforms that harmonise the requirements and capabilities of generators, grid operators, end users and electricity market stakeholders. In doing so, they optimise the efficiency of the entire system, reducing costs and environmental impact while simultaneously enhancing system reliability.

Recycling: The end-of-life collection rate for electricity network infrastructure that contains copper could reach 80%-90%; in the EU, this already stands at 75%-80%.¹¹³

^p A summary of the highest-priority levers based on academic literature and practitioner analysis; this is not comprehensive.

^q Barriers and opportunities are explored in the IRP's metals report series (*Recycling Rates of Metals*, *Metal Recycling and Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles*).

^r As well as Pillar 2 solutions, this is normally the result of systemic solutions in Pillar 1.

^s Summary of highest-priority levers based on academic literature and practitioner analysis, not comprehensive.

Electricity production (~20% of transition material demand by 2050)^t

Solar PVs:

Increased efficiency: Greater PV efficiency can help to reduce material intensity and land use per gigawatt (GW) of installed capacity – for example, adding a thin layer of perovskite to solar PV cells can improve their power conversion efficiency rates.¹¹⁴

Restoration: Whether it makes more economic sense to replace or refurbish ageing solar PV panels will depend on both the local context and the specific condition of the panels. However, restoration options aimed at extending the lifetime of solar PV panels have already shown promising results in the United States.¹¹⁵

Recycling: Industry experts estimate that by 2040/50, around 70%/90% of solar panels will be collected for recycling at end of life.¹¹⁶

Wind:

More intensive use: A shift to larger wind turbines would lead to lower material intensity per GW of installed capacity or per terawatt of electricity production.¹¹⁷

Lifetime extension: Turbine blades sometimes fail and need replacing earlier than expected, so there is a need for new manufacturing methods aimed at extending blade life. Advanced drone and robotic inspection, diagnostic, maintenance and repair techniques would also help to avoid early replacement.¹¹⁸

Lightweighting: Turbine blades made of innovative materials such as carbon fibre are lighter, more durable and easier to recycle.¹¹⁹

Once again, there are economic opportunities to be gained from implementing Pillar 2 solutions. Mining and refining companies can profitably diversify into circular business models such as transition materials reuse and recycling, and materials as-a-service.¹²⁰ However, as the secondary supply on which these models depend will take some time to come online, the immediate solutions described in Pillar 1 are indispensable initial steps in the interim.



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^t This is a summary of the highest-priority levers based on academic literature and practitioner analysis; it is not comprehensive.

PILLAR 3: SUPPLY TRANSITION MATERIALS IN ACCORDANCE WITH THE HIGHEST ENVIRONMENTAL AND SOCIAL STANDARDS

Even if both Pillar 1 and Pillar 2 solutions are fully implemented, an increase in transition materials will be needed to build high-performing provisioning systems powered by clean energy.^{121, 122} This expanded supply must not come at the expense of the planet; and safeguards for Indigenous Peoples and local communities that act as stewards of biodiversity hotspots should be strengthened, not removed.

By minimising all risks along the transition materials value chain, policymakers can align expanded supply with sustainable development, maximising the environmental and social benefits through high-value activities such as precision mining and increasing local value capture by building capacity for downstream processing and manufacturing.¹²³ As outlined above, the extraction and refining of transition materials are highly geographically concentrated and are therefore vulnerable to local shocks. Supply resilience can be strengthened by increased geographical diversification of these activities. Again, this presents a major economic opportunity for lower-income countries.¹²⁴

Additionally, by minimising negative impacts along the value chain – and validating this through enhanced transparency – the substantial incoming investment in transition materials can be channelled towards projects that meet highest possible environmental and social standards. Value chains with high environmental, social and governance standards are more robust: not only does this reduce the climate and biodiversity-related risks to which they are exposed, but they are also more likely to be able to access lower-cost finance (eg, low-interest funding from the United Nations and the World Bank). For countries that wish to ramp up and diversify production, proactively ensuring that new projects adhere to high environmental and social standards should enhance the benefits for local communities and reduce the risk of delays.¹²⁵ Quality refining infrastructure and recycling capacity could also present opportunities for recovering transition materials from used products, with high environmental and social standards.

To minimise the environmental impact of mining, actors along the transition materials value chain should subscribe to the SDLO, as recommended in the IRP's 2020 report entitled *Mineral Governance in the 21st Century*.¹²⁶ The SDLO is a framework that aims to improve the net societal benefits of mining through enhanced environmental and social governance and transparency.^{u, 127} The SDLO seeks to strengthen links between the extractive sector and local economies, improving local value capture and ensuring that mining and refining contribute positively to the achievement of environmental and social goals.¹²⁸ The implementation of the SDLO should be the joint responsibility of source countries and countries along the transition materials value chain.¹²⁹

Existing policy proposals already encompass several Pillar 3 solutions, as they seek to enhance environmental outcomes and boost supply chain resilience. For example, at its fifth session, the UN Environment Assembly adopted a resolution entitled 'Environmental Aspects of Minerals and Metals Management' (UNEP/EA5/Res12), which aims to improve environmental impacts across mineral and metal lifecycles and tasks the United Nations Environmental Programme with

setting up regional consultations on solutions implementation.¹³⁰ Similarly, the proposed EU Critical Raw Materials Act and the G7 Five-Point Plan for Critical Minerals Security both seek to improve environmental and social governance along the transition materials value chains.^{131, 132}

While this policy recognition is encouraging, some key Pillar 3 solutions are still missing. Transition material strategies should establish sustainable investment paths and ensure fair value distribution along the value chain. Source countries can benefit from incoming investment but should also capture value by undertaking downstream processes locally. Countries are increasingly refining mined materials themselves and are capturing greater value by exporting the higher-value products that result. For example, in the DRC, the Manono Project will produce and export refined primary lithium sulphate.¹³³

In conclusion, while Pillar 3 actions are essential, securing the supply of new transition materials is a lengthy (up to 15 years for some materials) and potentially environmentally and socially impactful process.^{134, v} More immediate and more systemic solutions (as captured by Pillars 1 and 2 respectively) are thus also required.

^u This could minimise unintended consequences – for example, for water scarcity – explored by Schomberg et al (2021).

^v In the past decade, the average lead time from discovery to production was over 16 years for copper and at least five years for lithium (IRP, *Financing the Extractive Sector*, forthcoming).

ACTIONS CAN BE REFINED AND BECOME MORE IMPACTFUL IF THEY ARE GUIDED BY SCIENTIFIC MODELLING

Currently, major models on future demand for transition materials do not account for demand mitigation measures; those that do mainly feature efficiency improvements in energy infrastructure and changes to EV size. However, this is unrealistic: based on current projections – and even with ambitious plans for expanded supply – major transition materials such as copper and lithium are likely to suffer supply-demand gaps over the coming decade (Figure 6).¹³⁵

Although there is abundant literature on the material needs of the energy transition (eg, from the IEA and the ETC),^{136, 137} a dedicated modelling exercise which explores the potential impact of different solutions is lacking. Decision makers in policy and industry would benefit from a better understanding of the quantitative outcomes that may result from different solutions when setting priorities and determining their action strategies – and explaining them to the electorate. For example, how large would the future land-use footprint of lithium mining be with improved mining processes and technologies, but no demand mitigation solutions? How would maximising the circularity of lithium reduce environmental impact and how long would it take for a substantial secondary supply to become available?

The most crucial missing piece is a quantification of the potential impact of changes to the most energy-intensive provisioning systems (see Pillar 1). For example, what impacts could be avoided by limiting the increase in demand for transition materials while also achieving a just energy

transition? Would this mean that deep-sea mining could be avoided?

Building on the research conducted for *GRO24* – which models system-wide Pillar 1 solutions, but not their consequences for transition materials – we offer a blueprint for future studies to quantify the effect of these shifts on demand for transition materials and their environmental and supply chain implications (Figure 12).

A full and just energy transition is a baseline scenario (Scenario 0 in Figure 12). There is no question that this is necessary; but if today's production and consumption patterns continue, the spiralling impacts of unchecked demand for transition materials will likely create additional unintended environmental pressures. Therefore, this modelling blueprint presents our proposed solution pillars as layered scenarios. Modelling based on this framework would explore the global environmental and supply chain implications of Pillar 1, 2 and 3 solutions. The modelling should also take account of the time it would take to realise solution benefits. For example, it may be one or two decades before a reliable secondary supply of certain transition materials can be established, meaning that some Pillar 2 solutions may take time to be fully realised. By contrast, systems such as mobility and housing can be optimised through Pillar 1 solutions straight away. The implications for human wellbeing should also be modelled – in particular, to avoid unintended consequences for low-income countries or citizens. Enhanced overall human wellbeing should be the desired outcome.

Figure 12. A modelling framework for quantifying the impact of solutions across all three pillars

Systemically reducing Transition Material demand through Pillar 1 is indispensable, and likely to be most effective

A suggested blueprint for modelling research to understand Transition Material futures: **Likely changes in Transition Material-associated impacts in different decoupling scenarios**

Impacts caused by Transition Material mining, processing, trading, use and disposal	Scenario 0 (Baseline): A full energy transition, within current consumption and production patterns	Scenario Pillar 3 Supply the necessary Transition Materials with highest environmental and social standards	Scenario Pillar 2 Use all Transition Material circularity levers	Scenario Pillar 1 Optimise delivery of human needs in energy and material-intensive systems	Key Not affected by pillar's solutions
Overall energy use		?	?	?	
Overall environmental impacts		?	?	?	
Supply chain resilience		?	?	?	
Overall societal impacts Human wellbeing		?	?	?	
	...misses opportunities for overall resilience	...cleaning transition material value chains is the first crucial step	...activating circular economy levers is important, but alone may not be enough to address risks	...makes the economy fundamentally more resilient and creates largest system-wide co-benefits	Significantly improved by pillar's solutions

*Qualitative hypotheses based on literature review

If today's production and consumption patterns continue, the spiralling impacts of unchecked demand for transition materials will likely create additional unintended environmental pressures.

CONCLUSION: PRIORITY ACTIONS FOR GLOBAL GOVERNANCE

The energy transition is imperative for all countries – whether high or low income, producer or consumer. Achieving this is in everyone's interests and will enhance sustainability and resilience. As countries undergo the energy transition, they must focus on the dual goals of decoupling and the sustainable management of all materials – not just those which are critical from an energy perspective. This approach is crucial if the attendant environmental and social challenges are to be effectively addressed and managed.

As discussed in this opinion piece and in previous work by the IRP,^{138, 139} **decoupling** – which breaks the links between unchecked resource use, economic development, human wellbeing and environmental impacts – is essential. As the upcoming *GR024* will demonstrate, Pillar 1 solutions that mitigate the underlying drivers of demand by optimising high-performing provisioning systems are the most effective way to achieve decoupling while accelerating and facilitating the energy transition.

Some Pillar 2 and 3 solutions have already been recognised by policymakers, but their scope could be more ambitious, ensuring that opportunities are not missed. The focus of our recommendations is on shaping the governance arrangements for implementation.

Deep, overarching system shifts are necessary in order to make Pillar 1 a reality, as summarised in the 2022 IRP Co-Chair opinion piece *Making Climate Targets Achievable*.¹⁴⁰ However, these solutions are largely missing from most discussions on the energy

transition and transition materials. There must also be a focus on building awareness of the benefits and potential afforded by these solutions. The optimised delivery of human needs is essential if the energy transition is to be aligned with the goal of decoupling. In this regard, the following governance measures will be key.

To capitalise on opportunities across all three pillars and avoid being locked into high levels of material demand in the future, leadership should pursue the following concrete actions, among others:

Pillar 1 action recommendations:

- Give science a clear mandate (eg, from the G20) to develop resource use targets (within a specific timeframe) to reduce overall material and energy demand through efficient housing and mobility systems. This is important in order to decouple energy and resource use from wellbeing and environmental impacts, to ensure that humanity can thrive within a safe operating space. It will also facilitate the energy transition and help mitigate demand for transition materials. National policymakers should plan for absolute or relative decoupling depending on their level of current resource use and their requirements to meet essential human needs.
- Encourage investment in optimised housing and mobility systems by national governments, multilateral financial institutions (eg, the World Bank) and supranational groups (eg, the G7 and G20).

Pillar 2 action recommendations:

- Prioritise circular economy measures for transition materials where supply-demand gaps are most likely (ie, lithium and copper).^w It will take some considerable time before secondary supply can meet a significant proportion of future demand for transition materials
- Overcome barriers to lithium battery recycling by standardising recycling and improving economic viability – for example, by establishing a taskforce comprised of industry representatives and scientists to align on a common battery recycling process.
- Maximise function per unit of copper in electricity grids through capacity building for lifespan extension and reuse at end of life.
- Establish a multilateral commitment to sharing research, innovation and best practice on circular economy strategies for transition materials.

Pillar 3 action recommendations:

- Agree on operating standards for mining that are aligned with sustainable development – for example, by implementing the SDLO recommended by the IRP. Extraction, refining and recycling projects which can prove that they comply with the SDLO should be able to qualify for climate finance.¹⁴¹
- Ensure mandatory levels of transparency through the disclosure and monitoring of environmental and social risks across the entire transition materials value chain.

While **we know enough now to take immediate action, priorities can be further refined through scientific work**. The immediate direction of travel is clear, but scientific modelling on the effectiveness and regional specificity of different solutions is still nascent and must improve. This would enable precise targeting of the most effective solutions for transition materials. Providing funding for scientific modelling efforts should be a priority for government groups such as the G7 and G20.

^w It will take some considerable time before secondary supply can meet a significant proportion of future demand for transition materials, but circular economy strategies can mitigate the need for virgin transition material extraction.

Endnotes

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For more information, contact:
Secretariat of the International Resource Panel (IRP)
Economy Division
United Nations Environment Programme
1 rue Miollis - Building VII - 75015 Paris, France
Tel: +33 1 44 37 14 50 - Fax: +33 1 44 37 14 74
Email: unep-irpsecretariat@un.org
Website: www.resourcepanel.org
Twitter: @UNEPIRP
LinkedIn: International Resource Panel (IRP)