CRITICAL MINERALS AND THE GREEN TRANSITION

DO WE NEED TO MINE THE DEEP SEAS?

ENVIRONMENTAL JUSTICE FOUNDATION

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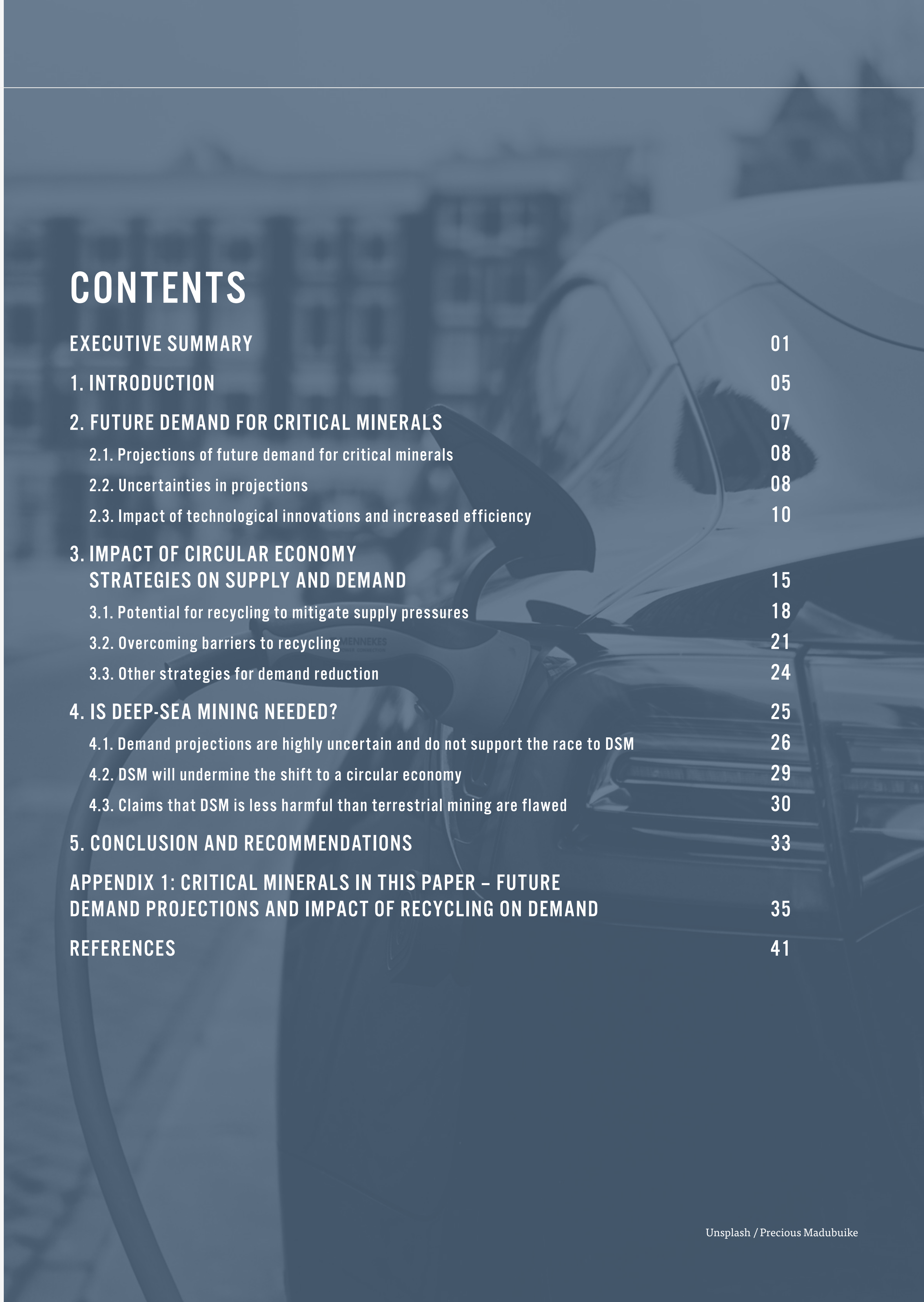
ACRONYMS AND ABBREVIATIONS

BEV	Battery electric vehicle
CCZ	Clarion-Clipperton Zone
DSM	Deep-sea mining
EASAC	European Academies' Sciences Advisory Council
EOL	End-of-life
EPR	Extended producer responsibility
ESG	Environmental, social and governance
EU	European Union
EV	Electric vehicle
GM	General Motors
IEA	International Energy Agency
ISA	International Seabed Authority
ISF	Institute for Sustainable Futures
LFP	Lithium iron phosphate
LMO	Lithium manganese oxide
LI-AIR	Lithium-air
LI-ION	Lithium-ion
LI-S	Lithium-sulphur
NA-ION	Sodium-ion
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt oxide
NORI	Nauru Ocean Resources Inc.
PV	Photovoltaics
REE	Rare earth element
SSB	Solid-state battery
TMC	The Metals Company



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EXECUTIVE SUMMARY

PROPONENTS OF DEEP-SEA MINING (DSM) CONTEND THAT DSM IS NEEDED TO FILL A FUTURE GAP IN THE SUPPLY OF CRITICAL MINERALS REQUIRED FOR THE CLEAN ENERGY TRANSITION.

THIS BRIEFING EXPLAINS WHY THIS ARGUMENT IS FLAWED.

We conclude that DSM is not needed to fulfil future demand, if the right investments are made now and regulatory frameworks implemented to accelerate the deployment of green technology chemistries that do not depend on supply-constrained minerals – many of which already exist and are growing rapidly in market share – and to promote the transition to a circular economy model to close any future supply gap.

Opening up a new mining frontier in the deep sea is not guaranteed to curb the financial incentives for land-based mining, nor would it selectively eliminate the most harmful examples of terrestrial extraction. It would also fail to supply many of the critical minerals needed for renewable energy and storage technologies. Instead DSM would significantly increase humanity's footprint on the planet's ecosystems, threaten to undermine the urgently needed shift away from unsustainable, linear modes of consumption, and create significant environmental and social injustices.

ON THE FUTURE DEMAND FOR CRITICAL MINERALS

While there is general consensus that demand for critical minerals will grow in the coming years due to the requirements of the clean energy transition, forecasts vary widely. Models of future demand are based on multiple assumptions, which are often characterised by a high degree of uncertainty.

Battery technologies are developing rapidly, which will significantly impact the mix of minerals that will be used, and thus levels of demand, in the coming years.[1] Price increases due to supply constraints will likely incentivise technological advances and drive raw materials substitution, impacting long-term demand.[2]

Lithium-iron-phosphate (LFP) batteries that require neither nickel nor cobalt – two of the main minerals targeted by the DSM industry – already account for around one-third of the share of the global passenger electric vehicle (EV) market. A recent study found that current (LFP) and future (Lithium-air, Lithium-sulphur, and solid-state) cobalt-free technologies could reduce cobalt cumulative demand by 62% and 41%, respectively, by 2050.[3] Several technologies are in the early stages of development, such as sodium-ion batteries, that could further reduce demand for critical minerals.

ON THE IMPACT OF CIRCULAR ECONOMY STRATEGIES ON SUPPLY AND DEMAND

A growing body of research highlights how future demand for critical minerals can be significantly reduced through the transition to a circular economy. Together, circular economy strategies, new technology and recycling could reduce cumulative mineral demand by 58% between 2022 and 2050 compared to a business as usual scenario, with recycled cobalt, nickel and manganese potentially supplying 80-90% of demand.[4]

Moving to a circular economy makes environmental and economic sense: circular economy strategies could cut global greenhouse gas emissions by 39% (22.8 billion tonnes) by 2030,[5] create a net increase of six million jobs by 2030,[6] including 700,000 in the EU alone,[7] while offering a US$ 4.5 trillion economic opportunity.[8]

Improving recycling is the most important strategy for reducing primary demand for minerals for EV batteries. The technological capability exists for recovery at rates exceeding 90% for copper, cobalt, lithium and nickel, yet is far from being fully exploited.[9]

Recycling capacities must be upscaled rapidly, to cope with the increase in low-carbon technologies reaching end-of-life (EOL) over the coming decade. With recycling often associated with net costs, there is an urgent need for the implementation of policies and regulatory frameworks to encourage higher recycling rates. Among other things, these must set out clear responsibilities and targets for recycling and use of recycled materials, and provide for improved collection, sorting and separation infrastructure.[10] If the necessary frameworks are implemented now, recycling of EV batteries and fuel cells is expected to take off rapidly from the mid-2030s.[11]

Additional demand reduction strategies must also be pursued in parallel with recycling. This includes legislation and policies to disincentivise private car ownership and make public transport more accessible.[12] Extending product lifetimes can also help mitigate supply pressure – a two-fold increase in battery lifetimes could nearly halve cobalt demand by 2050.[13]

ON WHETHER DEEP-SEA MINING (DSM) IS NEEDED

The assertion that DSM is needed to meet future demand for critical minerals – made largely in isolation by the DSM industry itself – is increasingly contested.[14]

Mineral demand projections are highly uncertain and do not support the urgency with which proponents are pushing for DSM.[15] While supply constraints may be experienced for cobalt and nickel, both minerals are substitutable through alternative battery chemistries and have high potential recovery rates. Supply concerns are particularly high for lithium; however, lithium is not currently targeted by the DSM industry and, at trace levels, is not viable for extraction from polymetallic nodules – the focus of the majority of current DSM ventures.

Known reserves of lithium have also increased ten-fold over the past 25 years, while cobalt, nickel and copper reserves have more than doubled.[16] A study commissioned by the International Seabed Authority found that DSM could increase a metal surplus for copper and cobalt, potentially even depressing market prices and making DSM economically unviable.[17]

Recycling and other circular economy strategies can play a significant role in reducing demand for critical minerals and should be the primary focus of industry and government efforts. This would both increase supply chain security by reducing dependence on major suppliers such as China, and reduce the negative impacts of primary extraction. However, DSM risks undermining the shift to a circular economy, sidelining investment into sustainable solutions and perpetuating unsustainable linear modes of production and consumption.

Primary extraction will still, however, play a role in the clean energy transition – especially in the interim, before recycled metals become readily available.[18] While it is undisputed that terrestrial mining has negative environmental and social impacts, arguments that DSM is less environmentally and socially damaging than terrestrial mining are flawed in several respects. There are also critical knowledge gaps about the deep sea and the impacts of DSM that prevent fully informed, science-based decision-making.[19]

RECOMMENDATIONS

→ Establish legislative and policy frameworks to transform economies into circular models.

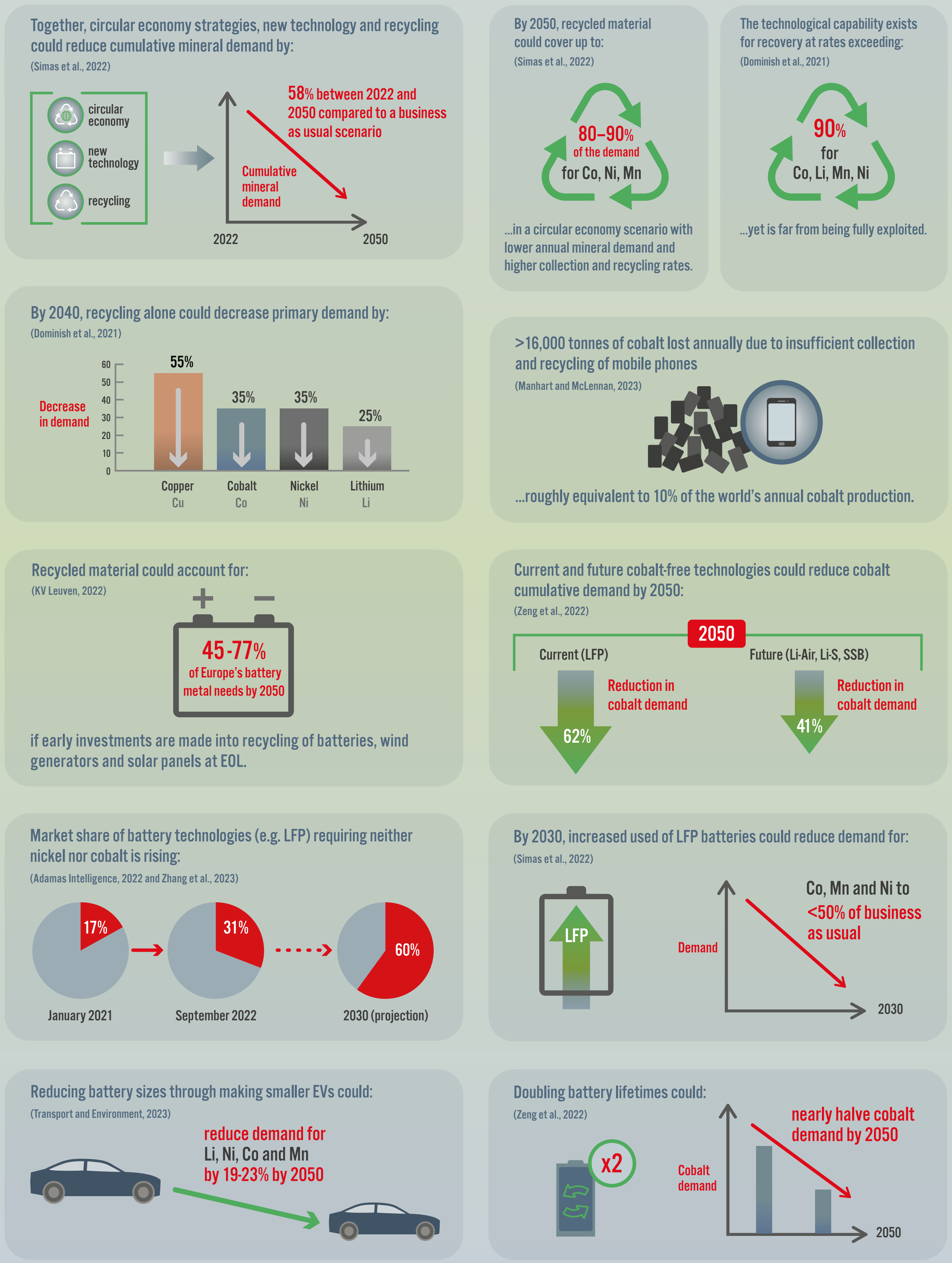
This should include the introduction of: EOL requirements and extended producer responsibility (EPR) for renewable energy technologies and electronics/electrical equipment; minimum standards for durability and repairability, including the right to repair; targets for the recovery of metals and recycled content of new batteries; clear regulations on reuse and repurposing of EV batteries to facilitate second-life uses;[20] restrictions on mineral-dependent, environmentally and socially damaging products, such as disposable e-cigarettes; and policies aimed at reducing individual consumption of products.

→ Implement fiscal measures to support the urgent transition to a circular economy with its associated economic opportunities.

This should include investments and taxation policies to encourage the development of large-scale recycling programmes and infrastructure, extension of product life cycles, improved energy and material efficiency, and public shared transport systems. Support must also be provided to accelerate the research and deployment of next generation technologies, including battery chemistries that do not depend on supply-constrained minerals, particularly cobalt.

→ With regard to the primary extraction of critical minerals, prioritise improving yields of existing mining operations and extraction of key materials from mining waste.

Any expansion or intensification of terrestrial mining must be carefully considered and take place within significantly improved and fully enforced environmental, social and governance (ESG) frameworks, with low-impact methods promoted. These must ensure human rights are respected throughout the lifetime of the mining operation, that waste is responsibly managed, and that impacts on biodiversity and the environment are limited. Emphasis must also be placed on mandatory requirements for robust supply chain due diligence and public disclosure, with a view to identifying human rights and environmental risks and implementing remedial actions where harm has failed to be prevented.[21]



01

INTRODUCTION

The 'green transition' away from fossil fuels and towards renewable forms of energy generation will see increasing levels of demand for critical minerals (see Box 1) over the coming decades. These minerals are used in clean energy technologies such as rechargeable batteries for electric vehicles (EV), solar photovoltaic (PV) generators, and wind power plants.

BOX 1: WHAT ARE CRITICAL MINERALS?[22]

Minerals, or more broadly, raw materials, might be described as 'critical' if they are considered to have a role in a country's strategically important economic sectors. A country may consider a mineral to be critical if it is especially dependent on imports of that material. There is no single list of defining criteria for 'critical' minerals or raw materials, with criteria and context varying substantially by country. However, criteria used to identify critical minerals often include the political and economic stability of producing countries, 'substitutability' of minerals and the production share by country.

Proponents of deep-sea mining (DSM) contend that DSM is needed to fill a future gap in the supply of critical minerals required for the clean energy transition.[23] This briefing explains why this argument is flawed. We review the growing body of research that casts doubt over the need for DSM and points to developments in green technologies and the ability of the circular economy to reduce primary demand for critical minerals and close the supply gap.

Our review focuses primarily on the following minerals: cobalt, copper, lithium, manganese, nickel, rare earth elements (REEs) and silver. These minerals are associated with some of the most significant potential supply constraints resulting from the energy transition.[24] In considering whether DSM is needed to 'close the supply gap' we frame our discussion around two key issues: (i) uncertainties in projections of future demand (**Section 2**); and (ii) the potential for demand to be met through the transition to a circular economy (**Section 3**). We bring these discussions together in **Section 4**, which considers additional arguments as to why DSM is not a credible way forward, including a brief consideration of the impacts of DSM compared to mining impacts on land. **Section 5** provides a brief set of recommendations based on the findings of this report – additional, more general recommendations are provided in our report on DSM, published in March 2023.[25]

Renewable energy development in the California desert by mypubliclands is licensed under CC BY 2.0.

02

FUTURE DEMAND FOR CRITICAL MINERALS

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2.1. PROJECTIONS OF FUTURE DEMAND FOR CRITICAL MINERALS

According to projections by the International Energy Agency (IEA), future mineral demand could more than double by 2030 if countries fully implement their national targets and ambitions set out in implementing legislation or Nationally Determined Contributions (NDCs).[26] In a scenario of net zero emissions by 2050, the IEA forecasts that demand will increase by three and a half times by 2030, to over 30 million tonnes, and six-fold by 2050 compared to the present day.[27] The World Bank forecasts particularly pronounced growth for cobalt, graphite and lithium, which may exceed current annual production by 4-5 times by 2050.[28]

EVs and battery storage are the main drivers of the growth in demand.[29] Low emission power generation, such as solar PV and wind turbines, makes an important contribution but is expected to increase more steadily compared to demand from EVs. EV lithium-ion (Li-ion) battery demand increased from 330 GWh in 2021 to 550 GWh in 2022.[30] In 2022, around 60% of lithium, 30% of cobalt and 10% of nickel demand was for EV batteries, increasing from around 15%, 10% and 2%, respectively, just five years earlier.[31] Battery demand for EVs is projected to account for 80-90% of demand for lithium and cobalt and 75%-85% for nickel by 2050.[32] EVs are the leading drivers of demand for the REEs neodymium and dysprosium, which are also used in permanent magnets in wind turbines.[33] Approximately 32% of neodymium and dysprosium is used in wind turbines and EVs.[34] Solar PV, meanwhile, is one of the largest drivers of demand for silver.[35]

2.2. UNCERTAINTIES IN PROJECTIONS

“[IEA PROJECTIONS] ARE INHERENTLY SUBJECT TO MODELLING ASSUMPTIONS ON FUTURE TECHNOLOGY DEVELOPMENTS, CHANGING BUSINESS MODELS AND BEHAVIOURAL ADAPTATIONS INFLUENCING MINERAL DEMAND, AMONG OTHER FACTORS. THE FUTURE IS FUNDAMENTALLY UNCERTAIN.”

– World Economic Forum (2022)[36]

While there is general consensus that demand for critical minerals will grow in the coming years, forecasts vary widely. An analysis by KU Leuven for the European metals association saw demand for the main metals required in the energy transition vary between 45 million and 80 million tonnes by 2050.[37] A recent paper by the European Academies’ Sciences Advisory Council (EASAC) highlighted uncertainties in nickel demand forecasts, which ranged between 24 and 100 million tonnes in three studies.[38] The IEA itself presents a range of potential figures, with demand for REEs, for example, projected to grow anywhere between three and seven times between 2020 and 2040.[39]

Models of future demand are based on multiple assumptions, which are often characterised by a high degree of uncertainty. This includes the relative contribution of different battery technologies over time, potentials for metal recycling up to 2050, and the overall size of the EV fleet (**Figure 1**).[40] Demand projections are undermined by uncertainties around the pace of progress in technological efficiency and transformational shifts in importance of certain technologies, among others.[41] Uncertainties are especially high for cobalt, with changes in battery sub-chemistries resulting in decreased demand and some chemistries requiring no cobalt at all,[42] a trend that is expected to continue (**Section 2.3**).[43]

“IF STATE-OF-THE-ART TECHNOLOGY AVAILABLE 10 OR 15 YEARS AGO WAS TAKEN AS THE BASIS FOR THE QUANTIFICATION OF FUTURE MATERIAL DEMAND, THE PICTURE COULD BE VERY DIFFERENT FROM THE ONE PRESENTED HERE.”

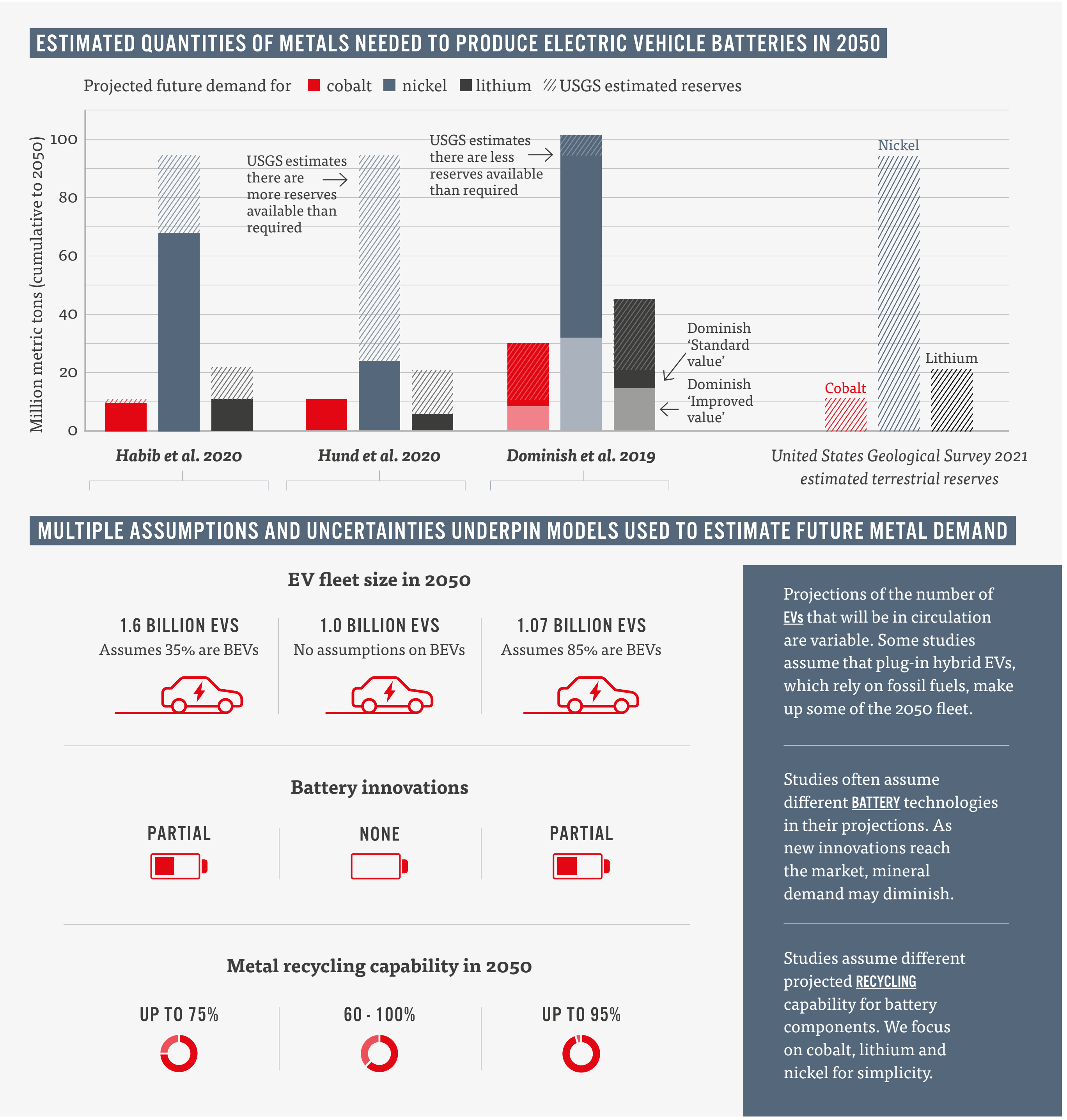
– Simas et al. (2021)[44]

> "UNCERTAINTIES ARE PARTICULARLY HIGH FOR COBALT: WHILE TODAY 57% OF THE GLOBAL COBALT PRODUCTION IS USED FOR [LITHIUM-ION] BATTERIES…THESE BATTERIES COME IN A NUMBER OF DIFFERENT SUB-TYPES, WHICH HAVE DIFFERENT COBALT CONTENTS WITH SOME REQUIRING NO COBALT AT ALL. SHIFTS IN SUB-TYPE PREFERENCES AND CHEMISTRIES ALREADY LED TO A DECLINING COBALT DEMAND PER BATTERY STORAGE CAPACITY AND IT IS EXPECTED THAT THIS TREND WILL CONTINUE"
>
> – Manhart and McLennan (2023)[45]

Demand projections often fail to consider the implications of policy shifts on future demand. Such shifts include investments in lifestyle change, public transport systems and cycling infrastructure, which can reduce the need for individual consumption of products such as electric cars and the minerals they require. For further discussion see **Section 3.3**.

FIGURE 1

Graphic contrasting the findings of three studies of future mineral demand due to EV batteries in 2050 and the underlying model assumptions (adapted from Miller, et al., 2021)[46]



2.3. IMPACT OF TECHNOLOGICAL INNOVATIONS AND INCREASED EFFICIENCY

Battery technologies are developing rapidly, which will significantly impact the mix of metals and materials that will be used, and thus levels of demand, in the coming years.[47]

As a World Bank study notes, it is almost impossible to forecast which battery technologies will be most used up to 2050.[48] Post-2030 both the scale of storage and the mineral composition of energy storage are highly uncertain, creating uncertainty not only around levels of demand but the specific minerals that will be needed for the low-carbon transition.[49] An analysis by the Rocky Mountain Institute (RMI) concludes that the evolution of battery technologies has initiated "a seismic shift in how we will organise energy systems as early as 2030", with new battery chemistries expected to compete with the prevailing lithium-ion (Li-ion) technology (see **Boxes 2 and 3**).[50] Breakthroughs in battery chemistries are unpredictable and can occur suddenly, with significant disruptive effects on the markets for key minerals. Future breakthroughs in sodium-ion (Na-ion) and solid-state batteries (SSB), for example, could displace the market for lithium-ion (Li-ion) batteries (which use nickel, cobalt and/or manganese) altogether.[51]

BOX 2: TRENDS AND INNOVATION IN RECHARGEABLE BATTERY CHEMISTRIES

INCUMBENT TECHNOLOGIES

Li-ion is currently the dominant chemistry in the global rechargeable battery industry.[52] Li-ion batteries are typically composed of a graphite anode (negative electrode), lithium-based liquid electrolyte, and a metal oxide cathode (positive electrode). The following cathode chemistries are prevalent (see **Figure 2** for an overview of their characteristics):

- **Lithium Nickel Manganese Cobalt Oxide (NMC/LiNiMnCoO2)**
  NMC is the most widely used chemistry in passenger EVs globally (as of H2 2022),[53] owing to its comparatively strong performance in cold weather and high specific energy.[54]
- **Lithium Iron Phosphate (LFP/LiFePO4)**
  LFP is a nickel- and cobalt-free chemistry of increasing popularity in both the passenger EV market[55] and for solar power storage due to its long life cycle, superior safety, thermal stability, relative lack of supply-critical metals and comparatively lower cost.[56] LFP batteries typically have a lower energy density than NMC,[57] though advancements are ongoing.
- **Lithium Nickel Cobalt Aluminium Oxide (NCA/LiNiCoAlO2)**
  NCA is the third most common chemistry in EVs owing to its high energy density.[58] While it has high specific energy and a long life cycle, it is held back by safety issues and a comparatively high manufacturing cost.[59]
- **Lithium Manganese Oxide (LMO/LiMn2O4)**
  LMO cathode material provides greater safety and fast-charging capabilities, but has a limited life cycle.[60] Its use is limited in EVs and is predominantly found in NMC/LMO blends.[61]
- **Lithium Cobalt Oxide (LCO/LiCoO2)**
  High specific energy means that LCO is widely used in mobile phones and laptops. LCO batteries are prone to overheating[62] and have a high relative cost due to the high cobalt content, and thus are not favoured for use in EVs.[63]

FIGURE 2

Characteristics of different cathode materials adapted from Faraday Institution (2023)[64]

MATERIAL FORMULA	ABBREVIATION	COST	ENERGY DENSITY	THERMAL STABILITY	CYCLE LIFE
$LiCoO_2$	LCO	High	Moderate	Poor	Good
$LiFePO_4$	LFP	Low	Low	Good	Good
$LiMn_2O_4$	LMO	Low	Moderate	Good	Poor
$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$	NMC622	High	High	Moderate	Good
$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	NMC811	High	High	Poor	Moderate
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	NCA	High	High	Poor	Moderate
$Li_{1.2}Mn_{0.48}Ni_{0.16}Co_{0.16}O_2$	LMR-NMC	Moderate	High	Moderate	Poor

EMERGING TECHNOLOGIES

The last decade has seen increasing interest in sodium-ion (Na-ion) batteries, owing to their use of cheaper and less supply-critical materials than conventional Li-ion units. Na-ion batteries have a similar design to Li-ion, but use sodium salts in the electrolyte and typically the cheaper and less supply-constrained aluminium – rather than copper – in the anode. The majority of the latest Na-ion EV battery designs, such as that of Chinese manufacturer CATL,[65] also do not contain either cobalt or nickel. Historically overlooked due to their inferior energy density, recent advancements in the technology mean that they are now being considered for both automotive and storage applications,[66] including lower end EVs.[67]

Lithium-sulphur (Li-S) batteries use a combination of a lithium metal anode and sulphur-containing cathode. This battery chemistry has a number of advantages: not only is sulphur more abundant and cost-effective than the minerals (such as cobalt) used in traditional Li-ion batteries, but it can also store a lot more energy than Li-ion based units of equivalent weight.[68] Given their technological similarity to Li-ion batteries, it is thought that they could be produced using existing factory infrastructure.[69] Despite these advantages, Li-S technology has historically been hindered by rapid degradation, severely shortening its lifespan. However, recent progress in halting corrosion has opened the door to commercially viable Li-S batteries in the years to come.[70] Given that they are expensive and are most appropriate for applications that require high energy density and where weight is at a premium, they are most likely to be used in large heavy goods EVs and in short-range aviation.[71]

There has also been an increasing amount of research and development of **solid-state batteries (SSBs).** While existing Li-ion and Na-ion battery designs use liquid electrolytes, SSBs replace this with a solid, typically ceramic, material. This switch not only increases safety owing to the flammability of liquid electrolytes, but it also allows for the use of lithium-metal or pure silicon anodes, which have the potential to greatly increase the battery's energy density.[72] Solid-state technology also enables new cathode chemistries; of particular interest to industry are developments in new Li-air batteries, which may offer an energy density of up to four times that of Li-ion.[73]

BOX 3: BATTERY TECHNOLOGY DEVELOPMENT AMONGST THE LEADING EV MANUFACTURERS

While Lithium Nickel Manganese Cobalt Oxide (NMC/LiNiMnCoO2) (NMC) batteries are currently the most widely deployed chemistry in EVs,[74] leading manufacturers are making rapid developments, including the pursuit of a range of alternative chemistries expected to increase safety and driving range. Industry players are investing in the search for new chemistries that avoid supply-constrained materials such as lithium and cobalt,[75] with a particular focus on improving the range of LFP batteries. Importantly, there is increasing collaboration between major manufacturers, which suggests a growing movement towards standardisation in battery design. Improved battery chemistry standardisation and labelling will be particularly important for the creation of successful recycling and second-life programmes.

- **TESLA** was the largest battery electric vehicle (BEV) manufacturer in 2022 by global units sold.[76] In 2021, the company made the decision to shift towards the use of LFP batteries in all of its standard-range vehicles and gradually phase out its use of the more critical-resource-heavy NCA and NMC chemistries.[77] In Q1 2022, nickel and cobalt-free LFP batteries were used in half of new EVs produced by the company.[78] Tesla currently sources LFP batteries from two Chinese manufacturers: CATL, a battery specialist, and BYD, a rival EV manufacturer. Tesla's move towards LFP technology, as well as partner institution research projects focusing on novel cobalt-free designs,[79] suggest that the company is now focusing on battery chemistries free of supply-constrained metals.

- **BYD**, the second largest BEV manufacturer in 2022, is increasingly using its 'Blade Battery' – an LFP chemistry – in its vehicles since the design's launch in 2020. Since mid-2021, all new BYD EVs are equipped with LFP batteries of this type.[80] Additionally, the company is seeking to use Na-ion batteries in some of its vehicles. The first iteration of BYD's sodium-based chemistries is expected to be a Na-ion/Li-ion hybrid and be introduced into a limited number of vehicles by the end of 2023.[81]

- **VOLKSWAGEN GROUP**, the third largest BEV manufacturer, uses a variety of battery chemistries across its various sub-brands, with Volkswagen- and Audi-branded EVs predominantly using NMC batteries in their current models. However, the group has made numerous strategic moves suggesting a shift towards alternative chemistries in future. In 2020, VW announced a partnership with Gotion High-Tech, a Chinese company that has been developing a long-range LMFP (Lithium Manganese Iron Phosphate) EV battery, and became the majority owner of the business in 2021.[82] A battery production cell hub built in partnership with Gotion is expected to enter operation in 2025.[83] Volkswagen Group is also the largest shareholder in QuantumScape, an American startup working on SSB technology. QuantumScape's SSB design is cathode agnostic, and as such allows for the development of solid-state LFP batteries. Its current aim is to deliver a test cell to EV manufacturers by end-2025, suggesting a potential commercial rollout in 2027.[84]

- **GENERAL MOTORS** was the fourth largest BEV manufacturer in 2022. Its BEV fleet across its various brands (Cadillac, Chevrolet, GMC, etc.) uses its 'Ultium' battery, which is currently based upon a low-cobalt Nickel Cobalt Manganese Aluminium (NCMA) cathode chemistry.[85] The addition of aluminium to its chemistry has helped the company to reduce the cobalt content in the current generation of Ultium batteries by around 70%.[86] The company has recently led an investment round in American startup Mitra Chem, which uses AI to speed up development of alternative battery chemistries, with the aim of using advanced LMFP technology in its Ultium batteries after 2025.[87]

- Most EV models manufactured by **HYUNDAI MOTOR**, the fifth largest BEV manufacturer globally in 2022, use NMC batteries. However, the firm has historically sold LFP-powered EVs in China in order to comply with local regulations, and has now signed an agreement with CATL for the supply of LFP batteries for EV models outside of China.[88] The company has also partnered with IonQ, an American business seeking to speed up Li-ion battery development using quantum computing.[89]

Shutterstock/The Image Party

Within the global passenger EV market, battery technologies that require neither nickel nor cobalt, such as LFP batteries, saw their market share rise to 31% in September 2022 compared to just 17% in January 2021 (**Figure 3**).[90] The global LFP battery market size is projected to double in the next five years, from US$ 17.7 billion in 2023 to US$ 35.5 billion in 2028,[91] reaching a 60% market share by 2030.[92] Chinese electric vehicle giant BYD has already announced plans to remove cobalt, nickel and manganese from its vehicle batteries entirely through a shift to LFP (**Box 3**),[93] while General Motors is also investing heavily in the development of second-generation iron-based chemistries, such as LMFP, that use neither nickel nor cobalt, to bring down the cost of EVs and make them more affordable for consumers (**Box 3**).[94] Cost concerns are considered a key driver of the resurgence of interest in more affordable LFP chemistries, both in China and elsewhere.[95]

It is likely that LFP's market share will grow further as concerns about the driving range of LFP-powered EVs are alleviated by second-generation chemistries with higher energy densities. Improvements in charging infrastructure in major markets – both in terms of number and charging speed – will also allow for EV batteries with iron-based chemistries to serve a wider range of consumer needs.[96]

"WE ARE WORKING WITH OUR CELL PRODUCERS TO LOOK AT LOW-COBALT TO COBALT-FREE CHEMISTRIES."

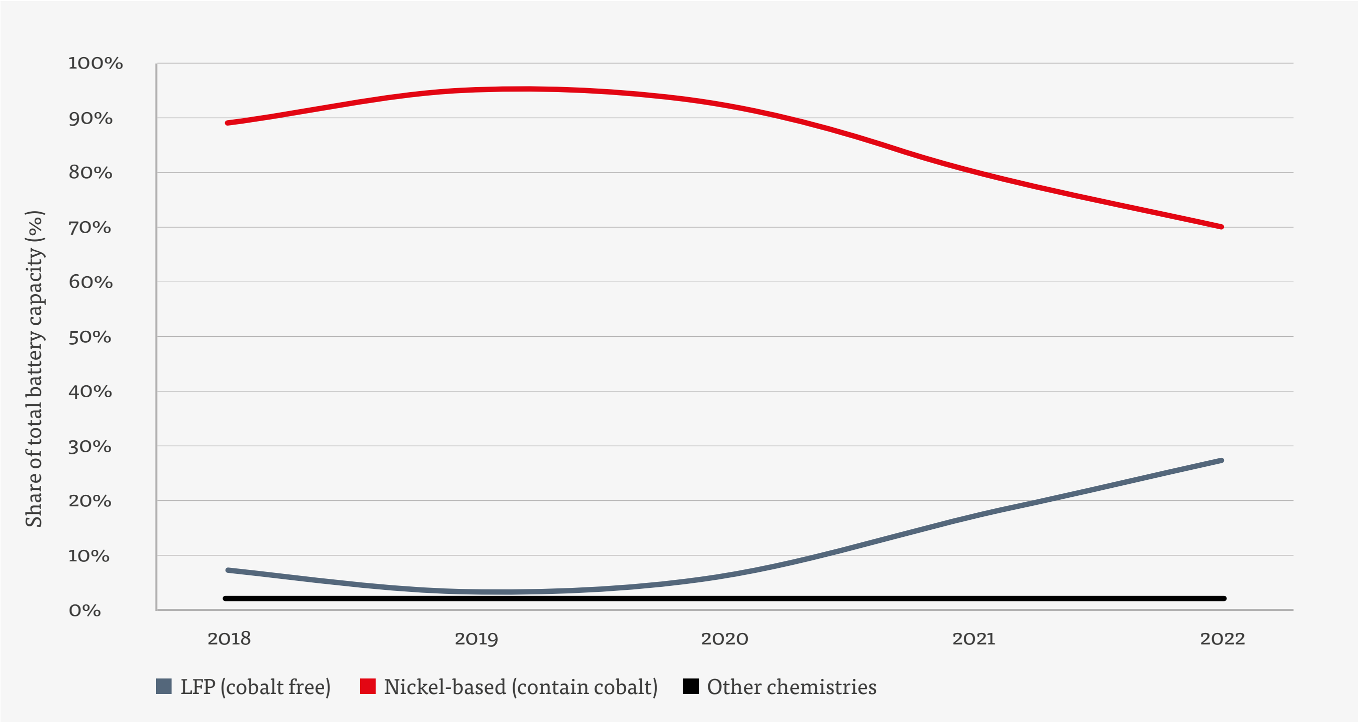
– David Rehnlund, Polestar[97]

A report by SINTEF, a non-profit research institution based in Norway, found that the increased use of LFP batteries (for example, due to resource prices or constraints, or decisions to reduce cobalt use to align with environmental or social standards), could reduce demand for cobalt, nickel and manganese to less than 50% of business as usual by 2030.[98]

FIGURE 3

Trends in market share of major EV battery chemistries for light duty vehicles (2018-2022)*

ELECTRIC LDV BATTERY CAPACITY BY CHEMISTRY 2018 – 2022



Source: adapted from IEA (2023)

*Cathode sales share is based on capacity.

"THERE ARE SIGNIFICANT DEVELOPMENTS IN BATTERY TECHNOLOGY WHICH ARE ELIMINATING THE NEED FOR NICKEL AND COBALT, WHICH ARE THE ONLY TWO METALS THAT REALLY MATTER FOR DEEP-SEA MINING […] TO INVEST IN A COMPANY […] INVOLVED IN DEEP-SEA MINING, IS BELIEVING THAT THERE WILL BE NO MAJOR TECHNOLOGICAL CHANGE IN BATTERY CHEMISTRY FOR THE NEXT 25 YEARS. AND THAT'S SIMPLY NOT CREDIBLE BECAUSE IT'S HAPPENING ALREADY."

– Victor Vescovo, Founder, Chief Executive, and Chief Submersible Pilot at Caladan Oceanic and Co-Founder of Insight Equity

Recent breakthroughs in Li-air batteries – which have the highest projected energy density of any next-generation battery technology – also propose designs which use no cobalt at all (see **Box 2**).[99] One study predicts that current (LFP) and upcoming (Li-air, Li-sulphur (Li-S), and solid-state) cobalt-free technologies could reduce cobalt cumulative demand by 62% and 41%, respectively, by 2050.[100] Forecasts of development timescales vary: one study saw the share of Li-S and Li-air batteries stabilising at 30% in 2040,[101] another projected the dominance of Li-S and Li-air batteries post-2030, accounting for 100% of the market share.[102] The 'Next-generation breakthrough' scenario modelled by the Faraday Institution assumes significant research breakthroughs in next-generation technologies occur at pace, with new battery technologies, such as Na-ion and Li-S, representing 50% of the market by 2050, while NMC and LFP together account for around 45% of the market share.[103]

"SOLID-STATE TECHNOLOGY, IN PARTICULAR, IS POISED TO MASSIVELY DISRUPT THE STORAGE INDUSTRY BY UNLOCKING NEW OPPORTUNITIES FOR CHEAP, SAFE, AND HIGH PERFORMING BATTERIES, INCLUDING NON-LITHIUM-BASED CHEMISTRIES."

– Tyson and Bloch (2019)[104]

Several technologies are in the early stages of development that could further reduce demand for critical minerals, such as Na-ion batteries for use in EV and stationary applications that do not require lithium[105] and operate with iron (rather than nickel) based chemistries in the cathode,[106] redox flow batteries for stationary applications that do not use any critical minerals,[107] and motor technologies for use in EVs that replace neodymium and dysprosium with lower cost REEs or alternative materials.[108] Supply chains for Na-ion batteries are already in place, with over 100 GWh of manufacturing capacity either currently operating or announced, almost all in China.[109]

"IN TERMS OF SUSTAINABILITY AND THE AVAILABILITY OF THE ELEMENTS NEEDED….THE TRANSITION TO SODIUM-BASED CHEMISTRIES WILL FLIP THE WHOLE GAME"

– David Rehnlund, Polestar[110]

Price increases due to supply constraints can also discourage adoption of certain technologies or drive raw materials substitution, decreasing long-term demand.[111] Following a reduction in Chinese quotas for exports of REE in 2010, the industry responded swiftly with the production of wind turbines with less or no REE (**Box 4**).[112] Increasing the use of permanent magnets for electric traction motors and wind turbine generators with low or no REE content could reduce total demand by one third, according to a report by SINTEF.[113]

BOX 4: IMPACT OF PRICE INCREASES ON MINERAL USE AND SUBSTITUTION

Increases in mineral prices can incentivise companies to innovate in the search for alternatives. A striking example is the case of magnets containing neodymium – a rare earth mineral – which are used in wind turbines.[114] It was generally assumed that neodymium magnets were very difficult to substitute, but after a reduction in Chinese REE export quotas led to a price peak for neodymium in 2010,[115] producers found ways to substitute 20-50% of neodymium magnets with other technologies.[116]

Similar experiences have been documented in the electric vehicle industry. Originally, Tesla used Nickel Cobalt Aluminium Oxide (NCA) cells in its cars. To increase its profit margins, it introduced the cheaper Lithium Iron Phosphate (LFP) battery cell free of nickel and cobalt. When prices for raw materials soared in early 2022, Tesla responded by increasing the number of cars manufactured with LFP batteries.[117]

"IT IS PLAUSIBLE THAT INCREASING COBALT PRICES WILL LEAD TO SUBSTITUTION EFFECTS TOWARDS OTHER METALS SUCH AS NICKEL, MANGANESE, IRON AND PHOSPHATE (WHICH ARE PARTLY ALREADY OBSERVED TODAY)."

– Manhart and McLennan (2023)[118]

03

IMPACT OF CIRCULAR ECONOMY STRATEGIES ON SUPPLY AND DEMAND

Dunsmuir Separated Bike Lanes 395 by Paul Krueger is licensed under CC BY 2.0.

A growing body of research highlights how future demand for critical minerals can be significantly reduced through the transition to a circular economy.

In a circular economy, extracted materials are used for as long as possible and, once a product's lifetime is over, are recovered and looped back into new products, thereby minimising waste.[119] The transition to a circular economy would have undeniably immense benefits, decreasing the need for primary mineral extraction and its associated social and environmental impacts, and increasing resilience in critical mineral supply chains.[120]

> "A CIRCULAR ECONOMY IS INCREASINGLY VIEWED IN TERMS OF SUPPLY CHAIN RESILIENCE. HAVING A RECYCLING INDUSTRY MEANS REDUCING SUPPLY CHAIN RISKS, THE IMPACT OF PRICE FLUCTUATIONS AND BOTTLENECKS IN MATERIAL AVAILABILITY"
>
> – Stephen Gifford, Faraday Institution[121]

A report by SINTEF found that demand for critical minerals can be met through the implementation of circular economy strategies (**Box 5**), including extending the lifespan of low-carbon technologies and substantially increasing recycling rates at EOL, along with advances in green technologies and material substitution. Together, these strategies could reduce cumulative mineral demand by 58% (from 690 million tonnes to 362 million tonnes) between 2022 and 2050 (**Figure 4**).[122]

BOX 5: CIRCULAR ECONOMY STRATEGIES

Reducing demand

This includes policies aimed at (i) driving lifestyle change and reducing individual consumption of products, for example, reducing private vehicle ownership through investments in urban planning, public transport and ride sharing, incentivising other modes of transport, such as cycling, through improved infrastructure, encouraging the adoption of energy saving practices in the home and shifting consumption towards reuse; and (ii) encouraging higher material and energy efficiency through promoting repurposing of waste streams as raw material, fostering shared use of products and repurposing, eliminating unnecessary or inefficient production processes, and upgrading domestic heating systems. Improving material efficiency is especially important for products with long lifetimes, such as solar PV.[123]

Extending product lifetimes

The aim is to keep extracted minerals in use for longer, for example, through: (i) improved urban planning to increase the lifespan of vehicles in use; (ii) investment in public transport to reduce individual car journeys; (iii) providing consumers with the information and spare parts they require to repair their electronic devices; (iv) introducing minimum standards for durability and repairability, including the right to repair, and (v) introducing incentives for corporations to renounce planned obsolescence and to offer 'lease' or 'pay-per-use' options.[124]

BOSTON PUBLIC TRANSPORT by foto_graffiti is licensed under CC BY-SA 2.0.

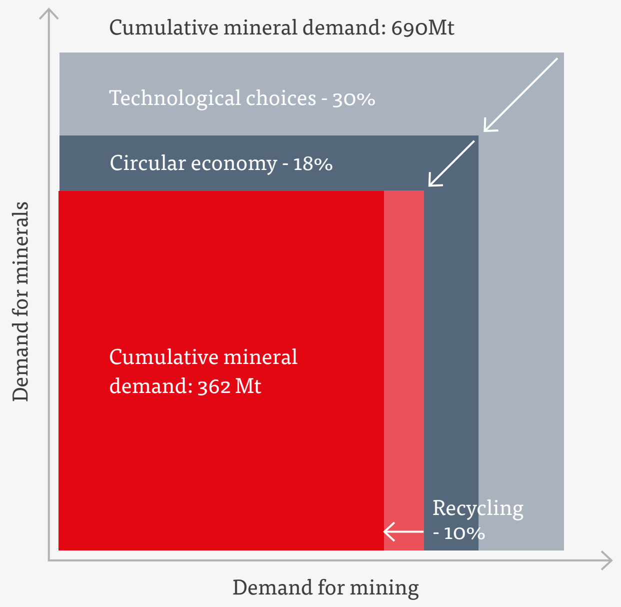
Recycling

The aim of recycling is to recover materials from EOL products and technologies and loop those materials back into production. Recycling companies are already working directly with the battery manufacturing supply chain, for example, SungEel High Tech in South Korea, owned by Samsung.[125] Tesla is also implementing a closed loop battery recycling programme – in 2022, Tesla recovered 2,300 tonnes of nickel, 300 tonnes of cobalt, 900 tonnes of copper and 300 tonnes of lithium from its EV batteries for recycling.[126]

In November 2021, Swedish battery manufacturer Northvolt announced that its recycling program, Revolt, had produced its first ever lithium-ion battery cell featuring an NMC cathode produced from metals recovered through the recycling of battery waste.[127] The performance of the battery was found to be on par with cells produced from virgin metals.[128] In 2022, Redwood Materials, an American startup created by an ex-Tesla co-founder, announced plans to construct a US$ 3.5 billion battery recycling facility in Nevada that by 2025 would produce enough material to supply batteries for around one million EVs.[129]

FIGURE 4

Summary of the reduction in mineral demand for low-carbon technologies installed between 2022 and 2050.



Technology and material substitution and upscaling of game-changing technologies can reduce mineral demand by 30%.

Implementation of circular economy strategies, reducing demand and extending the lifespan of low-carbon technologies, can reduce mineral demand by 18%.

Improving collection and recycling rates by 2050 for maximising mineral recovery from end-of-life low-carbon technologies can reduce demand for primary extraction by further 10%.

Recycled minerals can account for 20% of remaining mineral demand in the next three decades.

Simas et al. (2022)[130]

3.1. POTENTIAL FOR RECYCLING TO MITIGATE SUPPLY PRESSURES

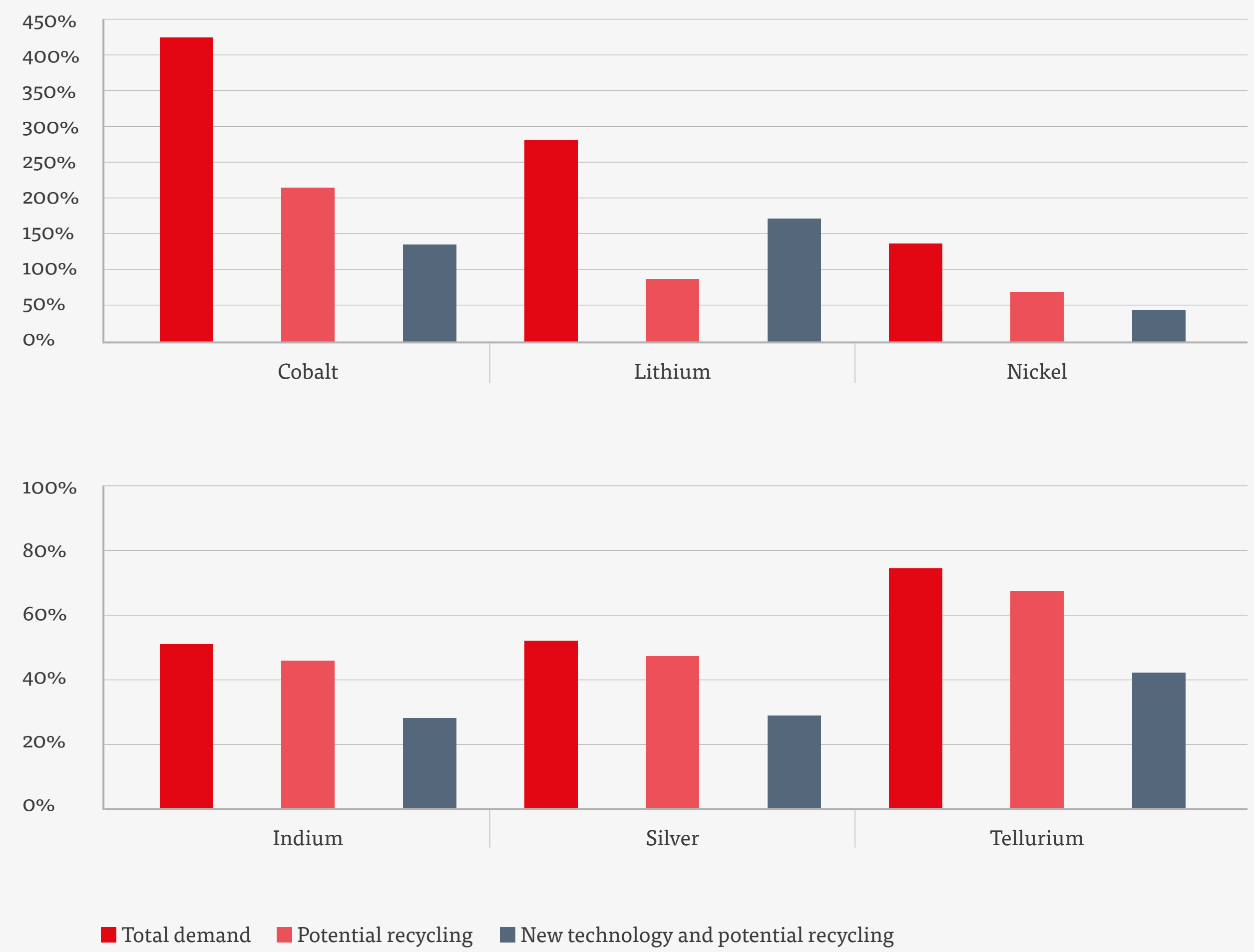
According to an analysis by the Institute for Sustainable Futures (ISF), primary demand for EV minerals can be reduced significantly through recycling (**Figure 5**).[131] ISF estimates that recycling alone could decrease primary demand for copper by 55%, cobalt and nickel by 35% and lithium by 25% by 2040, reducing the need for new mining.[132] Zhang et al. (2023) similarly estimate that recycling of discarded batteries could offset the need for primary resource extraction by 24-35% by 2050.[133]

SINTEF, in their projections, consider the potential contribution of recycling in combination with other circular economy strategies. They estimate that, in a circular economy scenario with lower annual mineral demand and higher collection and recycling rates, recycled material could cover up to 80–90% of the demand for cobalt, nickel and manganese in 2050.[134]

> "IN A CIRCULAR ECONOMY SCENARIO, WITH LOWER ANNUAL MINERAL DEMAND AND HIGHER COLLECTION AND RECYCLING RATES, RECYCLED COBALT, NICKEL AND MANGANESE COULD COVER UP TO 80–90% OF THE DEMAND FOR THESE MINERALS IN 2050."
>
> – Simas et al. (2022)[135]

FIGURE 5

Cumulative demand from renewable energy and storage by 2050 relative to reserves in three scenarios for selected battery metals (top) and solar PV metals (bottom)*. Adapted from Dominish et al. (2019)[136]



Potential metal demand is modelled against an ambitious scenario for a 100% renewable energy and transport system by 2050 that limits climate change to 1.5 degrees, and is based on current technologies. The scenario is considered by the authors as a 'high-demand scenario', as over time technologies may become more efficient or new technologies may emerge. Potential recycling is based only on EOL renewable energy and storage technologies and does not take into account recycled metals from other sources. It is noted that these projections were produced before the recent drive towards LFP chemistries, which are accounting for a rapidly growing market share in the EV passenger vehicle market, as explained in Section 2.3 (see also **Figure 3).*

“IMPROVING RECYCLING RATES WOULD LEAD TO THE EQUIVALENT OF BETWEEN 8.5 MILLION (FOR COBALT) AND 45.5 MILLION (FOR LITHIUM) AVOIDED BATTERY SALES OUT OF A TOTAL OF MORE THAN 200 MILLION ESTIMATED SALES IN 2040, EQUIVALENT TO 4% OR 22% OF TOTAL BATTERY SALES RESPECTIVELY”

– Dominish et al. (2021)[137]

The technological capability exists for recovery at rates exceeding 90% for copper, cobalt and nickel, and 80% for lithium, yet is far from being fully exploited (see **Figure 6** and **Appendix 1**).[138] Current recovery rates for lithium (and the REEs dysprosium and neodymium) are negligible (**Figure 6**); however, as mineral demand increases, the economic benefits of recovering these materials will likely justify recovery.[139]

FIGURE 6

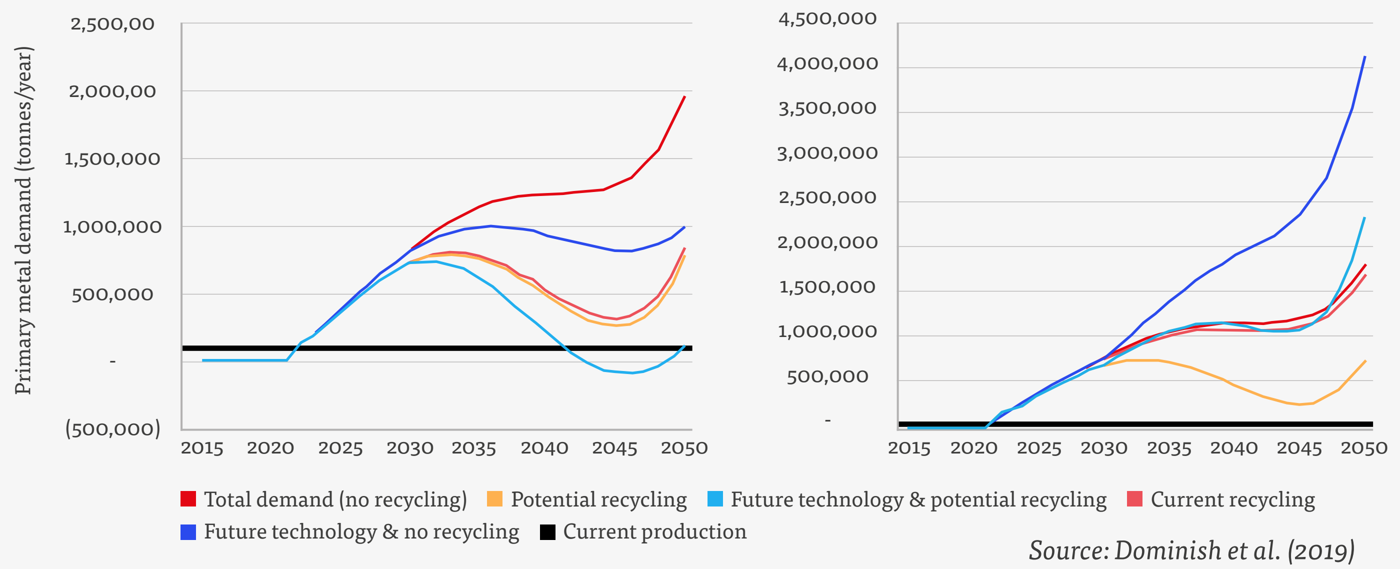
Mineral recovery rates for current, best available technology and used in the circular economy scenario by Simas et al. (2022)[140]

MINERAL	RECOVERY RATE (CURRENT)	RECOVERY RATE (BEST AVAILABLE TECHNOLOGY)	RECOVERY RATE (CIRCULAR ECOMONY)
Lithium	>1%	80%	80%
Cobalt	32-74%	96-99%	95%
Nickel	57%	90%	90%
Manganese	53%	95%	95%
REE - Dysprosium (from permanent magnets)	>1%	60%	60%
REE - Neodymium (from permanent magnets)	>1%	95-99%	95%
Platinum	60-70%	95-99%	95%
Copper	45-60%	100%	95%

Impacts are even greater when recycling is combined with a shift away from battery chemistries that use cobalt and nickel (see **Section 2**). While this would increase demand for lithium (Li-S batteries, for example, use around three times more lithium than Li-ion), there is significant potential to increase lithium recovery rates (**Figure 6**), which would partially offset this increase in primary demand (**Figure 7**).[141]

FIGURE 7

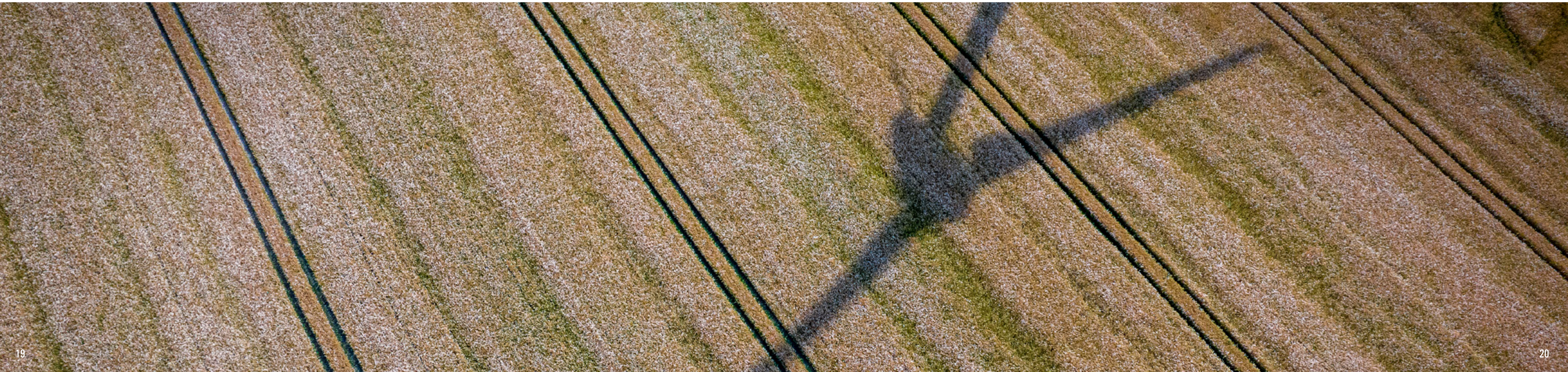
Annual primary demand from EVs and battery storage for cobalt (left) and lithium (right)*



Source: Dominish et al. (2019)

**Potential metal demand is modelled against an ambitious scenario for a 100% renewable energy and transport system by 2050 that limits climate change to 1.5 degrees, and is based on current technologies. The scenario is considered by the authors as a ‘high-demand scenario’, as over time technologies may become more efficient or new technologies may emerge.*

Potential recycling is based only on EOL renewable energy and storage technologies and does not take into account recycled metals from other sources. It is noted that these projections were produced before the recent drive towards LFP chemistries, which are accounting for a rapidly growing market share in the EV passenger vehicle market, as explained in Section 2.3.



EOL Li-ion batteries are considered the most viable source of secondary cobalt, lithium and nickel for EV applications.[142] However, urban and landfill mining also offer substantial opportunities (see **Box 6**) – each year more than 16,000 tonnes of cobalt are lost due to the insufficient collection and recycling of mobile phones, roughly equivalent to 10% of the world's annual cobalt production.[143]

BOX 6: URBAN MINING AND LANDFILL MINING

Urban mining and landfill mining can make a critical contribution to a circular economy. Urban mining describes the process of recovering materials from e-waste largely found in cities,[144] while landfill mining involves the recovery of materials from active and inactive landfills, of which an estimated 500,000 exist within the EU alone.[145]

Recovering metals from e-waste – one of the fastest growing global waste streams – has significant potential to reduce demand for virgin-mined metals. The United Nations estimates that, by 2030, global e-waste will reach a record high of 74.7 million tonnes.[146] Overall, just 17.4% of the e-waste generated worldwide is documented to be collected and recycled.[147] The raw materials contained in the EU's e-waste were worth US$ 12.9 billion in 2019[148] and more than three million tonnes of copper are estimated to be contained in EOL scrap.[149] The European Environment Agency estimates that slightly less than half of waste electrical and electronic equipment enters official treatment in the EU,[150] while an EU-funded consortium found that almost no critical raw materials are recovered because it is not deemed to be commercially viable.[151]

Research is increasingly highlighting the economic viability and potential of urban mining as an alternative to primary extraction. One study of urban mining in China, published in 2018, found that copper and gold could be recovered from e-waste streams at comparable costs to virgin mining of copper and gold ores, with potential application across a broader range of e-waste sources and metals extracted.[152] A similar study, published in 2022, found that urban mining of aluminium and copper has a lower cost than extraction from virgin mining: the cost of obtaining one tonne of copper or aluminium was found to be, on average, US$ 3,000 or US$ 1,660, respectively – significantly lower than the cost of virgin mining.[153] For copper, the greatest cost-benefits were associated with recovery from e-waste (as opposed to EOL vehicles and waste wires and cables), while for aluminium, cost-benefits were highest from recycling of EOL vehicles.[154] Critically, the 2022 study highlighted the need for regulation and policy to provide additional incentives, such as funding and subsidies, to encourage the transition away from virgin mining to urban mining and a circular economy.

FIVE MILLION SINGLE-USE VAPES ARE THROWN AWAY IN THE UK EACH WEEK, AMOUNTING TO 5,000 EV BATTERIES WORTH OF LITHIUM BEING DISPOSED OF EVERY YEAR.[155]

3.2. OVERCOMING BARRIERS TO RECYCLING

Recycling rates for EOL Li-ion batteries are currently low.[156] Barriers to recycling include the complexity, cost and resource intensive nature of recycling processes, and the lack of strong policy, legal and economic drivers to incentivise and support recycling, among other factors.[157] In many cases, the recycling of Li-ion batteries at EOL is associated with net costs and is therefore economically untenable in the absence of national and international frameworks assigning responsibilities and targets for take-back and recycling.[158] The volume of EV batteries reaching EOL is also insufficient at present to attract commercial investment into large-scale recycling operations without additional incentives or support.[159] Collection systems and infrastructure are undeveloped in many places, and progress to develop those systems has been slow.[160]

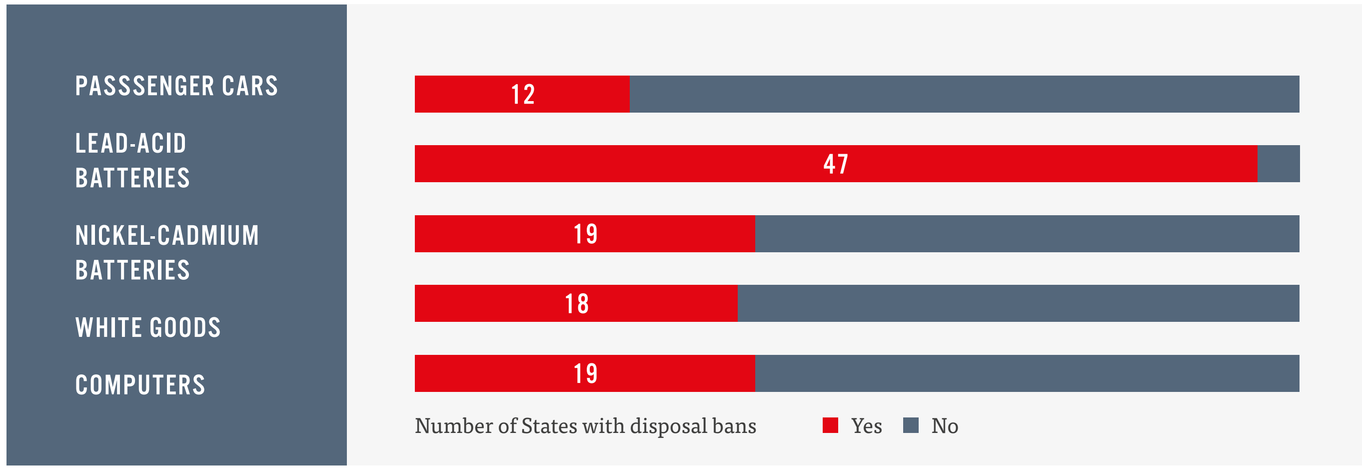
Recycling capacities must be upscaled rapidly, to cope with the expected increase in low-carbon technologies reaching EOL over the next decade. This will require, as a priority: (i) advances in recycling techniques and a reduction in costs, (ii) implementation of extended producer responsibility (EPR) to stimulate closed-loop recycling among manufacturers, (iii) improved collection, sorting and separation infrastructure for EOL Li-ion batteries, (iv) optimisation of infrastructure for high-value metal recovery to keep metals in use for advanced applications, (v) enhanced traceability and information sharing along battery supply chains, and (vi) battery designs that allow for easy dismantling and recyclability.[161]

While recycling rates are higher for materials from solar and wind power plants, at around 75%,[162] costs associated with collection, sorting and transport often makes recycling unviable, especially at lower collection volumes. This has necessitated regulation to mandate recycling, as seen with the inclusion of solar PV under the Waste Electrical and Electronic Equipment (WEEE) Directive in the EU.[163]

There is an urgent need for the implementation of policy and regulatory frameworks to support the collection and sound EOL management (including recycling) of batteries and other low-carbon technologies, and the subsequent use of recycled materials.[164] An example is the new EU Battery Regulation, which aims to promote a circular economy by regulating batteries throughout their life cycle (**Box 7**).[165] The United States Inflation Reduction Act (IRA) of 2022, which allows EV battery materials recycled in the US to qualify for subsidies (the Clean Vehicle Credit),[166] has reportedly triggered a recycling boom within the EV industry.[167] Yet additional policies and incentives are still considered necessary to accelerate establishment of a domestic battery recycling network and support the development of recycling technology.[168] One analysis highlighted critical gaps in US recycling legislation, with the majority of States allowing recyclable EOL products such as passenger cars, white goods and computers to be disposed of in landfill (**Figure 8**).[169]

FIGURE 8

Lax and non-uniform recycling requirements across the US limit the potential recovery of critical minerals from end-of-life products



Source: Espinoza et al. (2020) adapted from Northeast Recycling Council (2020)[170]

In the UK, analysts from the Faraday Institution have identified the need for a coherent 'waste hierarchy' strategy for Li-ion batteries, which addresses EOL management and covers recycling, reuse and repurposing of batteries, in order to process the estimated 16,500 tonnes of battery packs that will need to be processed by 2028.[171] A future recycling framework, they propose, should include inter alia EPR regulations to support the move to a circular economy model, eco-design criteria for recycling and remanufacturing, and mandatory chemistry labelling requirements for Li-ion batteries to facilitate sorting and separation for recycling.[172] The UK-based Faraday Institution is cooperating with the US Department of Energy's National Renewable Energy Laboratory (NREL) in support of joint research to develop new methods for the recycling of Li-ion batteries,[173] and, under its ReLiB project, is developing the necessary infrastructure to allow close to 100% of the materials in Li-ion batteries to be recycled.[174]

BOX 7: THE EU BATTERY REGULATION

The new EU Battery Regulation, adopted in July 2023, includes targets for recycled content in EV battery production, and incentivises the recycling of production waste and EOL batteries. Specifically, it:

- Sets out targets for producers to collect waste portable batteries (63% by the end of 2027 and 73% by the end of 2030) and waste batteries for light means of transport (51% by the end of 2028 and 61% by the end of 2031).
- Sets the target for lithium recovery from waste batteries to 50% by 2027 and 80% in 2031.
- Provides for mandatory minimum levels of recycled content for industrial, SLI batteries[176] and EV batteries. These are initially set at 16% for cobalt, 85% for lead, 6% for lithium and 6% for nickel.[177]

Several of the leading EV manufacturers are prioritising circular economy strategies, including product lifetime extension, second-life uses, and recycling, in recognition of the significant environmental and business benefits they provide. Examples of ongoing initiatives are provided in **Box 8**.

If the necessary frameworks are implemented now, recycling of EV batteries and fuel cells is expected to take off rapidly from the mid-2030s.[178] BloombergNEF expects the battery recycling market to grow six-fold by 2030, with around five million tonnes of EOL batteries available for recycling in 2035, enough to provide 15-30% of metals used in battery production.[179] The Li-ion battery recycling market alone is forecast to reach US$ 19.9 billion by 2030, at an average annual growth rate of 7.6%.[180] A regional assessment by KU Leuven found that recycling could be Europe's major supply source for most transition metals after 2040, assuming early investments are made into recycling capacity to deal with batteries, wind generators and solar panels as they reach EOL.[181] Recycled material could account for an estimated 45-77% of Europe's battery metal (lithium, nickel and cobalt) needs by 2050, and exceed Europe's needs for rare earth elements (dysprosium, neodymium, praseodymium) after 2040, the study found.[182]

> **"RECYCLING IS EUROPE'S MAIN OPPORTUNITY TO IMPROVE ITS LONG-TERM SELF-SUFFICIENCY AND COULD PROVIDE 45-65% OF EUROPE'S BASE METALS NEEDS BY 2050, UP TO 77% FOR BATTERY METALS, AND A RARE EARTH ELEMENTS SURPLUS."**
>
> – KU Leuven (2022)[183]

BOX 8: CIRCULAR ECONOMY STRATEGIES IMPLEMENTED BY MAJOR EV MANUFACTURERS

Tesla

In its Impact Report 2022, Tesla underlined its aim to 'reduce its reliance on primary mined materials and contribute to a more positive environmental footprint through battery and cell recycling'.[184] In 2022, none of the batteries returned to Tesla through fleet returns or manufacturing scrap went to landfill,[185] with 2,300 tonnes of nickel, 300 tonnes of cobalt, 900 tonnes of copper and 300 tonnes of lithium recovered for recycling.[186] Tesla's battery cell recycling facility at its Nevada site has demonstrated the capacity to recycle 100 metric tonnes of battery metals per week. The company is also prioritising extension of battery lifetimes as environmentally and economically superior to recycling, both in its new designs and through updates to existing vehicles to help improve battery efficiency.[187] Tesla is also investing in 'scalable battery recycling technology for nickel- and iron-based cathode chemistries, including recovery and re-use of lithium'.[188]

Andreas Salewsky, plant manager Volkswagen Group Components Salzgitter, and local works council chairman Dirk Windmüller commence operation of the Salzgitter recycling plant.

Volkswagen Group

Volkswagen Group

Volkswagen Group has entered into a strategic partnership with recycling group Umicore for battery recycling and opened its first pilot facility for recycling high-voltage vehicle batteries at its Salzgitter site at the start of 2021. Its objective is the recovery of lithium, nickel, manganese and cobalt in a closed loop, with a recovery rate of more than 90% in future. The factory has been designed to recycle up to 3,600 battery systems per year in a pilot operation.[189]

General Motors

General Motors (GM) has also been working to build circular economy principles into its battery supply chains.[190] In order to improve its recycling capabilities, GM made a strategic investment in Lithion, a Canadian battery recycling business. Lithion is able to recover 95% of battery materials using exclusively renewable energy, reducing greenhouse gas emissions by over 75% and water usage by over 90% when compared to the mining of equivalent virgin battery materials.[191] Lithion's new demonstration plant has capacity to process 7,500 metric tonnes of Li-ion batteries each year.

> **"I'M VERY OPTIMISTIC THAT 10 YEARS FROM NOW A LOT OF THESE MINERALS WILL BE RECYCLED AND FED BACK INTO THE VALUE CHAIN, SIMILAR TO HOW PLATINUM FROM CATALYTIC CONVERTERS IS RECYCLED TODAY."**
>
> – Phil Lienert, General Motors[192]

Amongst other major EV manufacturers, BYD has also advocated for the development of a circular economy.[193] The firm repurposes its used batteries for renewable energy grid storage across the globe.[194] Hyundai Motor is also looking to increase the range of second-life uses for its EV batteries, with its sub-brand Kia already having agreed to supply waste batteries to German rail operator Deutsche Bahn for the creation of an energy storage system.[195] In August 2023, Jaguar Land Rover announced plans to use second-life Jaguar I-PACE batteries in energy storage systems for wind and solar power.[196] BMW, Bosch, and Vattenfall, a Swedish state-owned multinational power company, used 2,600 battery modules recovered from over 100 BMW cars to build a 2MW energy storage facility in Hamburg.[197] Mercedes-Benz is constructing a battery recycling plant in Kuppenheim, Germany, which is set to achieve recovery rates of over 96% using an innovative mechanical-hydrometallurgical process, with an annual capacity of 2,500 tonnes.[198] It is also pursuing grid-storage applications of second-life batteries through its subsidiary Mercedes-Benz Energy.[199]

3.3. OTHER STRATEGIES FOR DEMAND REDUCTION

Research highlights the importance of pursuing other demand reduction strategies in parallel with developments in recycling (**Box 5**). This includes policies to disincentivise private car ownership and make public transport more accessible.[200]

Research by clean transport campaign group, Transport and Environment, found that policies to incentivise a switch to smaller, more affordable entry-level EVs, adopt innovative battery chemistries (see **Box 2**) and reduce private car journeys, could cut demand for key metals lithium, nickel, cobalt and manganese by 36-49% by 2050.[201] Reducing battery sizes through making smaller EVs was the most effective policy, reducing demand by 19-23%, while reducing private car journeys could deliver a further 7-9% in reductions, the study found.[202] According to another study in North America, car sharing has the potential to reduce personal vehicle usage and rates of ownership. The study found that each car shared could take between 9 and 13 private cars off the road.[203]

Another study which considered the impact of extending product lifetimes found that the doubling of battery lifetimes could nearly halve cobalt demand by 2050.[204] Several EV manufacturers are working to develop batteries with lifespans of up to around 20 years (compared to the current 8-15 years),[205] while EOL EV batteries can also have a second life in grid storage applications, with potential lifetimes of around 12 years.[206]

SINTEF estimates that reducing car ownership and extending battery lifetimes by five years could reduce annual battery mineral demand by 10-20% between 2030 and 2040, reaching up to 50% of annual demand by 2050.[207] For copper, in particular, lifetime extension of power generation technologies, EVs and batteries has the potential to make the greatest contribution to reducing demand.[208]

> **"RATHER THAN INVESTING SUBSTANTIAL PUBLIC AND PRIVATE FUNDING ON TECHNOLOGIES TO EXTRACT METALS FROM THE DEEP OCEAN, WE SHOULD BE INVESTING IN DEVELOPING SHARING AND CIRCULAR ECONOMIES AND LIFESTYLE CHANGE – INNOVATING TECHNOLOGY AND SYSTEMS THAT REDUCE THE USE OF RAW MATERIALS."**
>
> Deep-sea Conservation Coalition[209]

04

IS DEEP-SEA MINING NEEDED?

Carlos Díaz / Ocean Image Bank

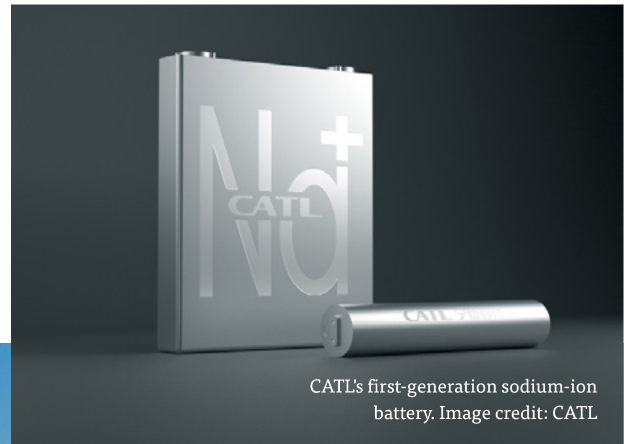
"THE PRESSURE FOR MINING IS DRIVEN BY INDUSTRY AND ECONOMIC INTERESTS RATHER THAN DEMANDS FROM THE TRANSITION TO A GREEN ECONOMY."

– EASAC (2023)[210]

The assertion that DSM is needed to meet future demand for critical minerals is increasingly contested[211] and flawed in several key respects. Made largely in isolation by the mining industry itself, it centres on two main contentions: (i) that land-based sources are incapable of meeting future demand, and (ii) that the environmental and social impacts of deep-sea mining are lower than those associated with terrestrial mining. We consider these arguments in turn below.

"THE NARRATIVE THAT DEEP-SEA MINING IS ESSENTIAL TO MEETING OUR CLIMATE TARGETS AND THUS A GREEN TECHNOLOGY IS MISLEADING. DEEP-SEA MINING WOULD NOT PROVIDE MANY OF THE CRITICAL MATERIALS NEEDED FOR THE GREEN TRANSITION AND OTHER HIGH-TECH SECTORS. IN ADDITION, RECYCLING RATES CAN BE VASTLY IMPROVED, AND FUTURE TECHNOLOGICAL INNOVATION HAS NOT BEEN ADEQUATELY CONSIDERED IN FORECASTS."

– Michael Norton, EASAC Environment Director.



CATL's first-generation sodium-ion battery. Image credit: CATL

4.1. DEMAND PROJECTIONS ARE HIGHLY UNCERTAIN AND DO NOT SUPPORT THE RACE TO DSM

"ADVANCES IN EV BATTERY TECHNOLOGY, AND THE ACCELERATING ADOPTION OF THESE TECHNOLOGIES, ARE LEADING TO THE REPLACEMENT OF EV BATTERIES DEPENDENT ON COBALT, NICKEL, AND MANGANESE. AS A RESULT, THE DEEP SEA MINING OF THESE METALS IS NEITHER NECESSARY, ECONOMICALLY ADVANTAGEOUS, OR ENVIRONMENTALLY ADVISABLE."

– Blue Climate Initiative (2023)[212]

As highlighted in **Section 2** of this briefing, demand projections are highly uncertain (**Figure 1**). Supply constraints may be experienced for cobalt and nickel in deep decarbonisation scenarios;[213] however, both minerals are substitutable through alternative battery chemistries[214] (which already account for a substantial market share) and have a high potential for recycling (**Figure 6**). Price increases due to future supply constraints may accelerate material substitution and advances in technology, confounding attempts to accurately forecast demand (see **Box 4**).[215] Demand for cobalt and nickel may even decrease between 2030 and 2050 as battery chemistries move away from these materials.[216]

"HIGHER LEVELS OF DEMAND WOULD LEAD TO HIGHER PRICES, CAUSING INCREASES IN SUPPLY BUT ALSO SUBSTITUTION OF OTHER MINERALS, WHERE TECHNICALLY POSSIBLE, AS WELL AS INNOVATION IN EFFICIENCY IMPROVEMENTS."

– Hund et al. (2020)[217]

Unsplash / Nicholas Doherty

DSM would not provide several of the critical minerals needed for the clean energy transition.[218] Supply concerns are particularly high for lithium, which would see significant increases in demand over the coming decades, but has few substitutes in EV batteries, other than through a shift to non-lithium chemistries (**Box 2** and **Table 1**). However, lithium is not currently a target of the DSM industry and is present only in trace quantities in polymetallic nodules – the focus of the majority of current DSM ventures – and the feasibility of extraction has not been proven.[219] Graphite is also a critical component of Li-ion batteries but cannot be generated from polymetallic nodules. Manganese, on the other hand, is present in significant quantities in polymetallic nodules, yet low-carbon technologies are expected to account for less than 5% of overall demand by 2050[220] and terrestrial supplies are considered sufficient across all demand scenarios.[221] Similarly, while polymetallic nodule mining can supply copper, demand from Li-ion batteries is negligible from a world market perspective, with battery production expected to have only marginal impacts on global copper demand and supply.[222]

DSM operations are largely unproven at commercial scale,[223] and require significant capital and operational expenditure.[224] The industry's long-term commercial viability rests heavily on whether the level and timing of future demand for the metals targeted by DSM operations will enable their profitable extraction from the seafloor. There remains considerable uncertainty in this regard: as of 2 October 2023, nickel, cobalt and copper were all trading below the assumed prices used by leading DSM proponent, The Metals Company (TMC), in their revenue model presented to investors in March 2021, by -0.6%, -35.7% and -13.9%, respectively.[225] Owing to various regulatory, technical and economic factors, timescales for the development of DSM operations are also highly uncertain and may not align with rates of increasing metal demand.[226]

"[LFP] NOW POWERS HALF OF ALL TESLA VEHICLES. THEY DON'T USE NICKEL AND COBALT AT ALL. TOYOTA'S MAIN PRODUCTION ROADMAP AND BYD OF CHINA ARE SHOWING THAT THEY ALSO ARE MOVING AWAY FROM NICKEL AND COBALT. THIS WILL CAUSE THE PRICES OF THOSE METALS TO FLATTEN OR EVEN [DECLINE], WHICH WOULD SIGNIFICANTLY UNDERMINE THE ECONOMIC REASON FOR DEEP-SEA MINING IN THE FIRST PLACE. SO THERE IS AN ECONOMIC AND VERY STRONG TECHNOLOGICAL ARGUMENT THAT IN THE NEXT 5 TO 10 YEARS THE METALS NEEDED FROM THE DEEP SEA FLOOR ARE NOT REALLY GOING TO BE NECESSARY."

– Victor Vescovo, Founder, Chief Executive, and Chief Submersible Pilot at Caladan Oceanic and Co-Founder of Insight Equity

Over the past 25 years, the number of known lithium reserves increased by a factor of ten, while cobalt, nickel and copper reserves have more than doubled.[227] A study commissioned by the International Seabed Authority (ISA) found that the terrestrial supply of key deep-sea metals is around 60 years of resources for nickel, 100 years for cobalt and more than 100 years for copper.[228] As such, DSM may only serve to contribute to a global surplus of these metals, potentially even depressing market prices and making DSM economically unviable.[229]

"A TRANSITION TOWARDS A 100% RENEWABLE ENERGY SUPPLY CAN TAKE PLACE WITHOUT DEEP-SEA MINING. METAL DEMAND ASSOCIATED WITH THE DOMINANT RENEWABLE TECHNOLOGIES EVALUATED IN THIS REPORT, EVEN ASSUMING VERY AGGRESSIVE GROWTH RATES UNDER THE MOST AMBITIOUS FUTURE ENERGY SCENARIOS, DO NOT REQUIRE DEEP-SEA MINING ACTIVITY."

– Teske et al. (2016)[230]


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TABLE 1

Overview of critical minerals considered, tentative demand projections, substitution and recycling potential, and EU supply risk (for additional detail, see **Appendix 1**)

MATERIAL	PROJECTED ANNUAL DEMAND COMPARED TO PRODUCTION (UP TO 2050)[1]	PROJECTED CUMULATIVE DEMAND IN 2050 COMPARED TO RESERVES[2]	MATERIAL SUBSTITUTABILITY[3]	RECYCLING POTENTIAL[4]	PRODUCED FROM POLYMETALLIC NODULES?	SUPPLY RISK (FOR THE EU)[5]
Cobalt	Demand > production	Demand > reserves	Yes	High	Yes	Moderate
Copper	Demand < production	Demand < reserves	Difficult	High	Yes	Very low
Lithium	Demand > production	Demand > reserves	Partly[6]	High	No	Low
Manganese	Demand < production	Demand < reserves	Yes	High	Yes	Very low
Nickel	Demand > production	Demand ~ reserves	Yes	High	Yes	Very low
REEs (neodymium and dysprosium)	Demand > production	Demand < reserves	Possible	High	No	Very high
Silver	Demand < production	Demand < reserves	Difficult	High	No	Very low

NOTES TO TABLE

[1] Based on Dominish et al. (2019).[231] Red represents metals for which demand exceeds current production in all scenarios. Green represents metals for which demand is less than current production in all scenarios. It is noted that Dominish et al. (2019) modelled potential metal demand against an ambitious scenario for a 100% renewable energy and transport system by 2050 that limits climate change to 1.5 degrees, and is based on current technologies. The scenario is considered by the authors as a 'high-demand scenario', as over time technologies may become more efficient or new technologies may emerge. Potential recycling is based only on EOL renewable energy and storage technologies and does not take into account recycled metals from other sources. It is noted that these projections were produced before the recent drive towards LFP chemistries, which are accounting for a rapidly growing market share in the EV passenger vehicle market, as explained in **Section 2.3** (see also **Figure 3**).

[2] Based on Dominish et al. (2019).[232] Red represents metals for which cumulative demand exceeds reserves in all or most scenarios. Orange represents metals for which cumulative demand exceeds reserves in the highest scenarios. Green represents metals for which cumulative demand is less than reserves in all scenarios. See **note 1** above regarding the model assumptions.

[3] Based on Manhart and McClennan (2023),[233] Simas et al. (2022)[234]

[4] Based on Simas et al. (2022)[235]

[5] Based on European Commission (2020)[236]

[6] Through a transition to non-lithium chemistries, such as sodium-ion, which is advancing rapidly.

4.2. DSM WILL UNDERMINE THE SHIFT TO A CIRCULAR ECONOMY

"DEEP-SEA MINING TO EXTRACT RAW MATERIALS WOULD PROMOTE THE CONTINUED EXPLOITATION OF EARTH'S RESOURCES, SUBSTANTIALLY EXPAND HUMANKIND'S "FOOTPRINT" ON THE PLANET, AND POTENTIALLY UNDERMINE EFFORTS TO TRANSFORM ECONOMIES BY PERPETUATING UNSUSTAINABLE, SINGLE-USE CONSUMPTION"

–Deep-sea Conservation Coalition (2022)[237]

Section 3 highlighted the substantial potential for recycling to reduce primary demand for critical minerals, particularly when combined with technological innovation and circular economy strategies, such as reducing consumption and increasing material efficiency. Recycling would help to increase resilience and supply chain security, while reducing primary extraction of raw materials and its associated environmental and social impacts. Current recovery rates of high-demand metals such as lithium, neodymium and dysprosium are less than 5% (**Figure 6**)[238] – an increase in recycling would improve production rates and reduce incentives to mine new sources of supply.[239]

"BETWEEN 25-55% OF PROJECTED DEMAND FOR [ELECTRIC VEHICLE] BATTERIES OVER THE NEXT TWO DECADES COULD BE OFFSET BY OPTIMIZING BATTERY METAL RECOVERY…[R]ECOVERY RATES OF ABOVE 90% ARE TECHNOLOGICALLY FEASIBLE FOR ALL FOUR METALS [COPPER, LITHIUM, NICKEL AND COBALT.]."

– Dominish et al. (2021)[240]

DSM risks undermining the shift to a circular economy, sidelining investment into sustainable solutions and perpetuating unsustainable linear modes of production and consumption. The "take, make, waste" approach of the traditional economic model has seen resource use triple since 1970[241] – equivalent to living off 1.75 Earths[242] – and is projected to double again by 2050 if business continues as usual.[243] Moving to a circular economy makes environmental and economic sense, aligning consumption with planetary boundaries, while increasing competitiveness, reducing dependence on scarce resources, stimulating innovation and creating employment. Studies suggest that circular economy strategies could cut global greenhouse gas emissions by 39% (22.8 billion tonnes) by 2030,[244] create a net increase of six million jobs by 2030,[245] including 700,000 in the EU alone,[246] while offering a US$ 4.5 trillion economic opportunity.[247]

"INTRODUCING SIGNIFICANT FLOWS OF NEW RESOURCES SUCH AS DEEP-SEA MINERALS WOULD ECONOMICALLY DISINCENTIVIZE THE SHIFT TOWARDS MORE SUSTAINABLE RESOURCE CONSUMPTION"

– Eléonore Lèbre, an expert in the circular economy and mineral exploitation at the University of Queensland[248]

4.3. CLAIMS THAT DSM IS LESS HARMFUL THAN TERRESTRIAL MINING ARE FLAWED

Primary extraction will still, however, play a role in the clean energy transition – especially in the interim, before recycled metals become readily available.[249] Terrestrial mining is already expanding to meet demand for renewable energy technologies, including cobalt developments in Australia, Canada and the US, and major new mines for REEs under development in Australia, Canada, Greenland, South Africa and the US.[250]

DSM proponents repeatedly point to the environmental and social advantages of DSM over terrestrial mining.[251] These assertions are flawed. The deep seabed is far from devoid of life: studies in the Clarion-Clipperton Zone (CCZ) – where mining exploration is currently concentrated – reveal high levels of diversity, rarity and endemism,[252] with an estimated 75% of animal species yet to be discovered in the sampled areas.[253] A recent study by the EASAC highlights the huge spatial and functional differences between areas required for terrestrial and marine mining.[254] Millions of square kilometres could be affected if DSM approaches its planned scale[255] – the impacts of sediment plumes, noise, light and vibrations would be felt well beyond the mined sites[256] and at shallower depths.[257]

Ellen Cuylaerts / Ocean Image Bank

Deep-sea ecosystems are extremely sensitive to (and slow to recover from) disturbance.[258] DSM could erase the oldest living organisms on the planet, including corals over 4,000 years old[259] and sponges up to 11,000 years old.[260] Biodiversity loss would be unavoidable, with taxa prone to extinction where restricted to mining areas.[261] The loss of mineral deposits, which have formed over millions of years, would impact the entire ecosystem: the 'Casper' octopus, for example, lays its eggs on sponges that grow only on nodules.[262] DSM risks disrupting the ocean's ability to sequester carbon and threatens fisheries and food security.[263] Studies in the Pacific – where tuna fisheries account for an average of 37% of government revenue[264] and fish contributes an estimated 50-90% of the animal protein consumed by a broad spectrum of coastal communities[265] – highlight significant overlap between tuna fisheries and areas subject to DSM exploration[266] and the potential for DSM to drive reductions in fish populations.[267] Scientists also warn of the potential for bioaccumulation of toxins in food webs, with possible risks for human consumption.[268] In contrast to terrestrial mining where mitigation and remedial measures are understood and widely implemented, there is no such possibility in the deep sea.[269]

"EUROPE'S SCIENCE ACADEMIES WARN OF THE DIRE CONSEQUENCES ON MARINE ECOSYSTEMS AND CHALLENGE THE BUSINESS CASE FOR DEEP-SEA MINING ON ANY SCALE UNTIL RECYCLING POTENTIALS HAVE BEEN FULLY EXPLORED."

– EASAC (2023)[270]

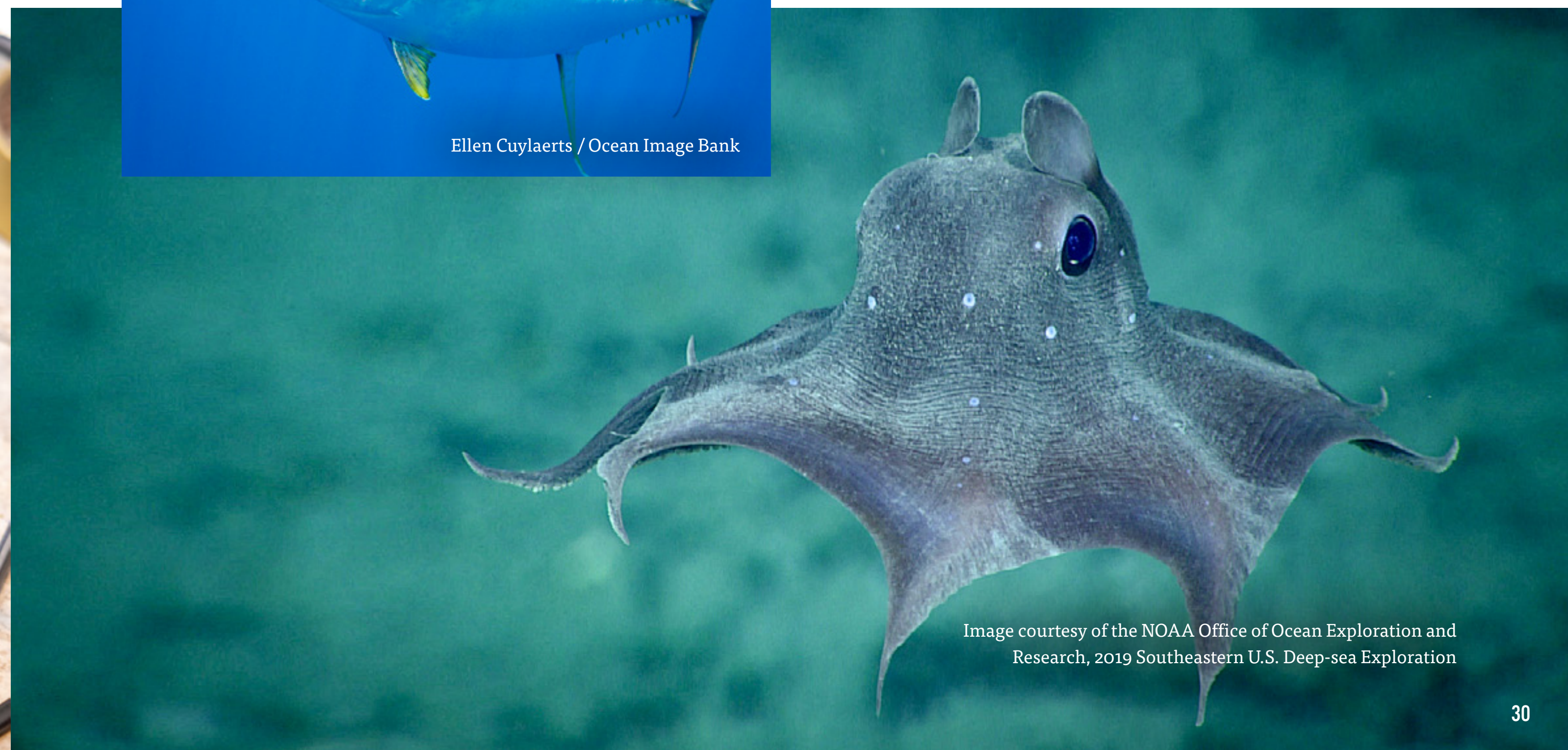


Image courtesy of the NOAA Office of Ocean Exploration and Research, 2019 Southeastern U.S. Deep-sea Exploration

Worryingly, the ISA lacks the capacity to monitor the impacts of DSM activities and enforce compliance with environmental protections. Recent events have exposed critical weaknesses in the system of self-reporting by DSM contractors: in October 2022, Nauru Ocean Resources Inc (NORI), a subsidiary of TMC, caused a spill of over 72,000 litres of seawater containing seabed sediment and metallic fragments while collecting polymetallic nodules in the CCZ. An ISA investigation concluded that TMC had failed to follow its own risk management procedures and had failed to adequately document the event, which may have impacted the accuracy of NORI's estimates of the extent of the spill and sediment concentration in the seawater.[271]

While the available scientific evidence establishes a clear risk of serious adverse environmental impacts, the extent and magnitude of the damage DSM would cause to the marine environment are unknown. Critical knowledge gaps that prevent fully informed, science-based decision-making remain.[272] In the absence of a solid baseline, environmental impact assessments are unreliable[273] and are likely to underestimate the extent and magnitude of environmental impacts.

"THIS IS A RUSH TO MINE MINERALS THAT MAY NOT BE THAT NECESSARY IN THE NEXT EVEN FIVE YEARS WHEN THE ENVIRONMENTAL DAMAGE COULD BE NOT ONLY EXTENSIVE BUT NEAR PERMANENT."

– Victor Vescovo, Founder, Chief Executive, and Chief Submersible Pilot at Caladan Oceanic and Co-Founder of Insight Equity

It is undisputed that terrestrial mining has negative environmental and social impacts – including pollution, heavy metal contamination of water and soils, and adverse health effects for workers and neighbouring communities[274] – and has been implicated in human rights abuses such as child labour.[275]

However, expanding mining activities into deep-sea areas of unparalleled fragility, vulnerability and biodiversity, where risks are high and impacts likely irreversible, is a false solution. Moreover, it is far from clear that DSM would curb financial incentives for land-based mining, nor would it selectively eliminate land-based operations with the lowest environmental and social performance.[276]

Rather, the emphasis should be placed on promoting energy efficiency and circular models of production and consumption, and any expansion or intensification of terrestrial mining must be carefully considered and take place within significantly improved and fully enforced environmental, social and governance (ESG) frameworks. Priority should be given to improving yields of existing mining operations and looping mining waste back into production. Indeed, research is ongoing into the feasibility of extracting minerals from mining waste such as tailings and process slag, for example the extraction of cobalt from copper mine waste in Australia, prompted by surging demand.[277] The metal ore mining industry discards an estimated 82% of exploited material as tailings and process slag, which still contains ore and other 'by-products' such as copper and nickel.[278]

"NOR WOULD [DSM] SELECTIVELY ELIMINATE LAND-MINING OPERATIONS WITH THE LOWEST ENVIRONMENTAL OR SOCIAL PERFORMANCE SINCE PRESSURE ON LAND-BASED MINES WOULD CORRELATE TO THEIR PRODUCTION COSTS RATHER THAN THEIR SUSTAINABILITY ATTRIBUTES."

– World Economic Forum (2022)[279]

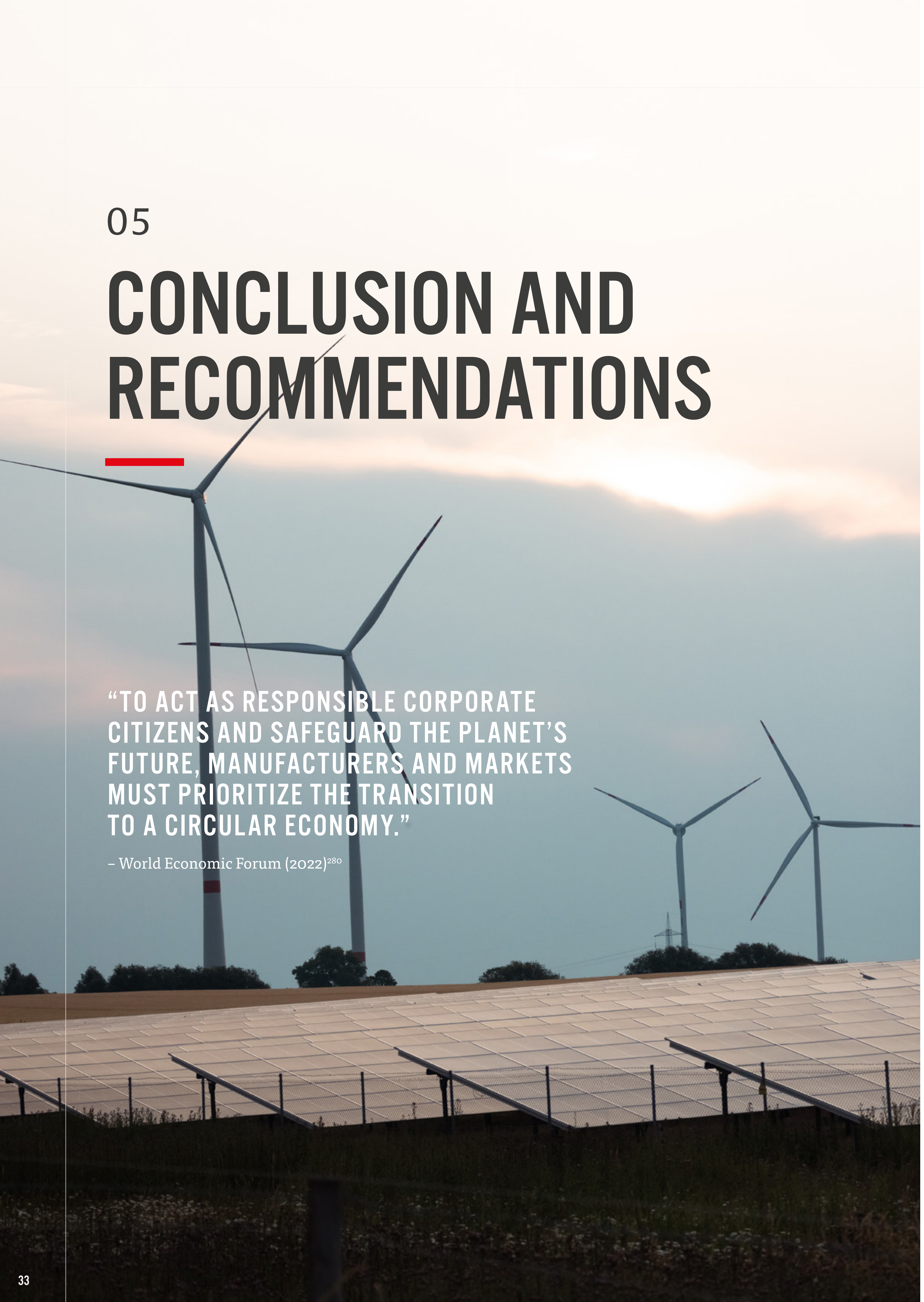
Unsplash / Paul-Alain Hunt

THE EXPANSION OF MINING ACTIVITIES INTO DEEP-SEA AREAS OF UNPARALLELED FRAGILITY, VULNERABILITY AND BIODIVERSITY, WHERE RISKS ARE HIGH AND IMPACTS LIKELY IRREVERSIBLE, IS A FALSE SOLUTION.

Tom Vierus / Ocean Image Bank

05

CONCLUSION AND RECOMMENDATIONS



> **“TO ACT AS RESPONSIBLE CORPORATE CITIZENS AND SAFEGUARD THE PLANET’S FUTURE, MANUFACTURERS AND MARKETS MUST PRIORITIZE THE TRANSITION TO A CIRCULAR ECONOMY.”**
>
> – World Economic Forum (2022)[280]

To achieve zero carbon emissions, we need to scale up efforts towards the clean energy transition.

But to open up the deep sea to excessive and devastating commercial mining cannot be the solution; nor can it be presented as the only viable way forward. On the contrary, deep-sea mining threatens to accelerate the catastrophe we are facing today, significantly expanding humanity’s footprint on the planet, while perpetuating unsustainable modes of production and consumption[281] and benefiting a narrow range of economic interests.

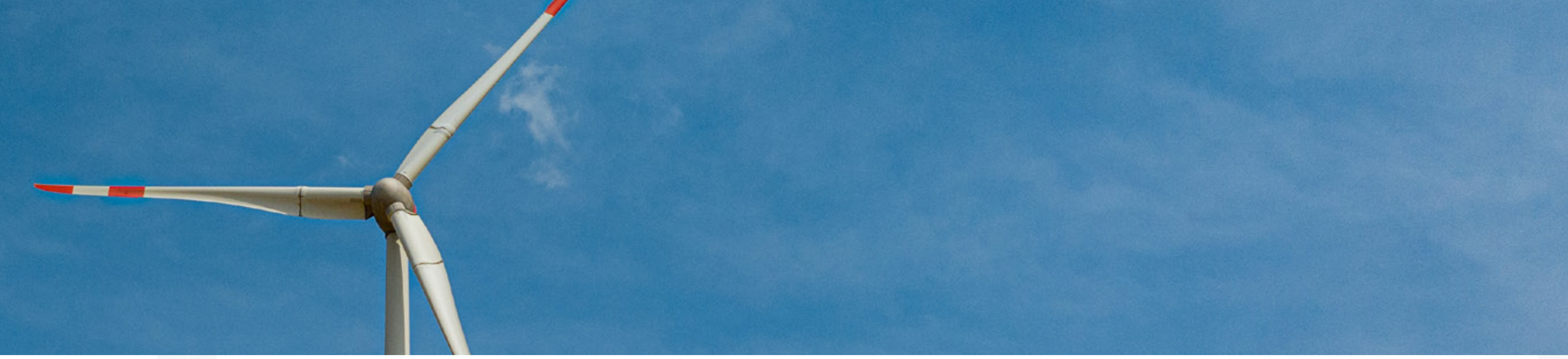
Rather than opening up a new frontier of mining expansion, investments should be targeted towards transitioning urgently to a circular economy.[282] This would reduce the need for primary extraction, whether in the deep sea or on land, while increasing resilience of supply chains and bringing substantial economic, social and environmental benefits.

TO ACCELERATE THE MOVE TO A CIRCULAR ECONOMY AND REDUCE DEMAND FOR THE CRITICAL MINERALS NEEDED FOR THE CLEAN ENERGY TRANSITION, WE RECOMMEND THAT NATIONAL GOVERNMENTS AND, TO THE EXTENT RELEVANT, LEADERS IN RELEVANT INDUSTRIES:

→ **Establish legislative and policy frameworks to transform economies into circular models.**
This should include the introduction of: EOL requirements and EPR for renewable energy technologies and electronics/electrical equipment; minimum standards for durability and repairability, including the right to repair; targets for the recovery of metals and recycled content of new batteries; clear regulations on reuse and repurposing of EV batteries to facilitate second-life uses;[283] restrictions on mineral-dependent, environmentally and socially damaging products, such as disposable e-cigarettes; and policies aimed at driving lifestyle change and reducing individual consumption of products.

→ **Implement fiscal measures to support the urgent transition to a circular economy with its associated economic opportunities.**
This should include investments and taxation to encourage large-scale recycling programmes and infrastructure, extension of product life cycles, improved energy and material efficiency, and public shared transport systems. Support must be provided to accelerate the research and deployment of next generation technologies, including battery chemistries that do not depend on supply-constrained minerals, particularly cobalt.

→ **With regard to the primary extraction of critical minerals, prioritise improving yields of existing mining operations and extraction of key materials from mining waste.**
Any expansion or intensification of terrestrial mining must be carefully considered and take place within significantly improved and fully enforced ESG frameworks, with low-impact methods promoted. These must ensure that human rights are respected throughout the lifetime of the mining operation, that waste is responsibly managed, and that impacts on biodiversity and the environment are limited. Emphasis must also be placed on mandatory requirements for robust supply chain due diligence and public disclosure, with a view to identifying human rights and environmental risks and implementing remedial actions where harm has failed to be prevented.[284]



APPENDIX 1

CRITICAL MINERALS IN THIS PAPER – FUTURE DEMAND PROJECTIONS AND IMPACT OF RECYCLING ON DEMAND

COBALT

Note: *demand uncertainties are particularly high for cobalt as Li-ion batteries account for 57% of demand yet chemistries are likely to change significantly up to 2050 (Manhart and McLennan, 2023).*[285]

MAIN CLEAN ENERGY APPLICATIONS

Energy storage.

ANNUAL DEMAND RELATIVE TO ANNUAL PRODUCTION

Annual demand is expected to exceed current annual production rates by 2030 (Dominish et al., 2019).[286]

Potential supply constraints until the mid-2030s (Zeng et al., 2022).[287]

Global annual demand in 2040 estimated at 310% of 2021 annual production (Faraday Institution, 2022 citing US Geological Survey, 2022).[288]

IEA estimates the share of total cobalt demand driven by clean energy technologies at 60-70% of total cobalt demand in 2040 in a scenario consistent with the goals of the Paris Agreement (IEA, 2021).[289]

World Bank projects annual demand from energy technologies will represent 460% of 2018 annual production in 2050 (Hund et al., 2020).[290]

However, others project a decline in demand as battery chemistries move away from cobalt (Teske et al., 2016).

CUMULATIVE DEMAND RELATIVE TO RESERVES AND RESOURCES

Cumulative demand from renewable energy and storage technologies could exceed reserves by 2050 (Zhang et al.,2023[291]; Dominish et al., 2019).[292]

Cobalt resources have more than doubled over the past 25 years (Simas et al., 2022).

Known terrestrial resources exceed projected cumulative demand (2015-2050) except under the most ambitious scenarios (Dominish et al., 2019).

CURRENT AND POTENTIAL RECOVERY RATE

Current recovery rate is around 32% (Hund et al., 2020) or up to 74% in some contexts (Simas et al., 2022).[293]

Recovery rates of 95% from batteries and EVs are possible (Dominish et al, 2019, 2021;[294]Manhart and McLennan, 2023).[295]

IMPACT OF RECYCLING ON FUTURE DEMAND

Recycling of Li-ion batteries has focused on recovery of cobalt due to high cobalt content and value of recycled cobalt (Simas et al., 2022).

Estimates of the impact of recycling on cobalt demand vary:

- Recycling could cut primary demand for cobalt by 35% by 2040 (Dominish et al., 2021).
- Considering current collection and recovery rates, recycled cobalt could provide up to 62% of annual demand in 2050 (Simas et al., 2022).
- Under a circular economy scenario with lower annual mineral demand and higher collection and recovery rates, recycling could cover up to 80-90% of cobalt demand by 2050 (Simas et al., 2020).
- Increasing recovery and recycling at EOL to 100% by 2050 would reduce cumulative demand for primary cobalt from energy technology by 15% (Hund et al., 2020).

SUBSTITUTABILITY

Yes - substitutable through shifts to other Li-ion sub-chemistries (e.g. LFP) with some loss of performance. However, state-of-the-art LFP battery energy density has improved considerably over the last decade, with this trend set to continue (Faraday Institution, 2023).[296]

Next generation of batteries to be commercialised in the coming decade are expected to be fully cobalt-free (Simas et al., 2022; Zeng et al., 2022). Cobalt and nickel chemistries may drop out of the market by 2030 (Teske et al., 2016).[297]

The use of alternative compositions for EV and stationary batteries could reduce total demand for cobalt by 40-50% between 2022 and 2050 (Simas et al., 2022).

Increased use of LFP batteries would see demand for cobalt fall below 50% of business as usual by 2030 (Simas et al., 2022).

COPPER

MAIN CLEAN ENERGY APPLICATIONS

Wind, solar PV, energy storage.

ANNUAL DEMAND RELATIVE TO ANNUAL PRODUCTION

Annual demand is expected to require less than 50% of current annual production by 2030 (Dominish et al., 2019).

Share of total copper demand driven by clean energy technologies is expected to exceed 40% of total copper demand in 2040 in a scenario consistent with the goals of the Paris Agreement (IEA, 2021).

World Bank projects annual demand from energy technologies will represent 7% of 2018 annual production in 2050 (Hund et al., 2020).

CUMULATIVE DEMAND RELATIVE TO RESERVES AND RESOURCES

Cumulative demand is expected to require less than 20% of reserves in all scenarios (Dominish et al., 2019; see also Manhart and McLennan, 2023; Wang et al., 2023).[298]

Copper resources have more than doubled over the past 25 years (Simas et al., 2022).

Known terrestrial resources exceed projected cumulative demand (2015-2050) under the most ambitious scenarios (Teske et al., 2016).

CURRENT AND POTENTIAL RECOVERY RATE

Current recovery rate is estimated at 28.5% (Hund et al., 2020) or 45-60% (Simas et al., 2022).

Dominish et al. (2019) estimates current recovery rates at 70% from batteries and EVs, 34% from solar PV and 95% from wind power.

Recovery rates of up to 95% are feasible for batteries and EVs, 81% for solar PV and 95% for wind power (Dominish et al., 2019; 2021).

IMPACT OF RECYCLING ON FUTURE DEMAND

Estimates vary:

- Recycling could cut primary demand for copper by 55% by 2040 (Dominish et al., 2021).
- Increasing recovery and recycling at EOL to 100% by 2050 would reduce cumulative demand for primary copper from energy technology by 26% (Hund et al., 2020).
- By 2050, recycled copper from EOL low carbon technology could constitute up to 85% of copper demand for new low-carbon infrastructure (Simas et al., 2022).
- Increasing recovery rates to 95% could generate enough recycled copper to cover almost 75% of annual demand by 2050 (Simas et al., 2022).

SUBSTITUTABILITY

Difficult to substitute due to its high electrical conductivity. However, some uses of copper can be substituted by aluminium, e.g. in overhead transmission lines.

LITHIUM

MAIN CLEAN ENERGY APPLICATIONS

Energy storage.

ANNUAL DEMAND RELATIVE TO ANNUAL PRODUCTION

Annual demand is expected to exceed current annual production by 2030 (Dominish et al., 2019).

World Bank projects annual demand from energy technologies will represent 488% of 2018 annual production in 2050 (Hund et al., 2020).

Global annual demand in 2040 estimated at 590% of 2021 annual production (Faraday Institution, 2022 citing US Geological Survey, 2022).

IEA estimates the share of total lithium demand driven by clean energy technologies at 90% of total lithium demand in 2040 in a scenario consistent with the goals of the Paris Agreement (IEA, 2021).

CUMULATIVE DEMAND RELATIVE TO RESERVES AND RESOURCES

Cumulative demand from storage technologies could exceed reserves (under more ambitious scenarios) by 2050 (Dominish et al., 2019).

Lithium reserves (around 16 Tg) fall short under high EV penetration rate (12-26 Tg) (Zhang et al, 2023).

Lithium reserves have increased 10-fold over the past 25 years and resources have increased 7-fold (Simas et al., 2022).

Known terrestrial resources exceed projected cumulative demand (2015-2050) under the most ambitious scenarios (Teske et al., 2016).

CURRENT AND POTENTIAL RECOVERY RATE

Current recovery rates are around 1% (Hund et al., 2020; Simas et al., 2022).

Potential recovery rates estimated at 80% (Simas et al., 2022) or up to 95% (Dominish et al., 2019; 2021).

IMPACT OF RECYCLING ON FUTURE DEMAND

Increasing recycling rates is considered essential to supply lithium for EVs although costs remain high (Simas et al., 2022). There is considerable potential to offset demand through increased recycling from minimal levels (Dominish et al., 2019).

Estimates of the potential impacts of recycling vary:

- By 2045, half of the annual lithium demand could be derived from recycled batteries (Simas et al., 2022).
- Recycling could cut primary demand for lithium by 25% by 2040 (Dominish et al., 2021).
- Increasing recovery and recycling at EOL to 60% by 2050 would reduce cumulative demand for lithium from energy technology by 26% (Hund et al., 2020).

SUBSTITUTABILITY

Yes, through shifts to battery types other than Li-ion or Li-metal (e.g. Na-ion batteries).

However lithium is currently used in most of the dominant battery technologies and those predicted to be of future importance (Dominish et al., 2019).

MANGANESE

MAIN CLEAN ENERGY APPLICATIONS

Wind, energy storage.

ANNUAL DEMAND RELATIVE TO ANNUAL PRODUCTION

Annual demand is expected to require less than 50% of current annual production by 2050 (Dominish et al., 2019).

World Bank projects annual demand from energy technologies will represent 4% of 2018 annual production in 2050 (Hund et al., 2020).

Supply is not expected to create a bottleneck for low-carbon technologies (Simas et al., 2022).

CUMULATIVE DEMAND RELATIVE TO RESERVES AND RESOURCES

Cumulative demand is expected to require less than 20% of reserves in all scenarios (Dominish et al., 2019; see also Simas et al., 2022 and Zhang et al., 2023).

Reserves are vast (Simas et al., 2022).

CURRENT AND POTENTIAL RECOVERY RATE

Current recovery rate is around 53% (Simas et al., 2022).

Recovery rates of 95% are feasible (Dominish et al., 2019; Simas et al., 2022).

IMPACT OF RECYCLING ON FUTURE DEMAND

Considering current collection and recovery rates, recycled manganese could provide up to 44% of annual demand in 2050 (Simas et al., 2022).

Under a circular economy scenario with lower annual mineral demand and higher collection and recovery rates, recycling could cover up to 80-90% of manganese demand by 2050 (Simas et al., 2020).

SUBSTITUTABILITY

Yes - substitutable through shifts to other Li-ion sub-chemistries (e.g. LFP, NCA) with some loss of performance.

The use of alternative compositions for EV and stationary batteries could reduce total demand for manganese by 40-50% between 2022 and 2050 (Simas et al., 2022).

Increased use of LFP batteries would see demand for manganese fall below 50% of business as usual by 2030 (Simas et al., 2022).

NICKEL

MAIN CLEAN ENERGY APPLICATIONS

Wind, solar PV, energy storage.

ANNUAL DEMAND RELATIVE TO ANNUAL PRODUCTION

By 2030, demand is expected to exceed current annual production rates (Dominish et al., 2019).

World Bank projects annual demand from energy technologies will represent 99% of 2018 annual production in 2050 (Hund et al., 2020).

Global annual demand in 2040 estimated at 150% of 2021 annual production (Faraday Institution, 2022 citing US Geological Survey, 2022).

IEA estimates the share of total nickel demand driven by clean energy technologies at 60-70% of total nickel demand in 2040 in a scenario consistent with the goals of the Paris Agreement (IEA, 2021).

However, others project a decline in demand as battery chemistries move away from nickel (Teske et al., 2016).

Additional demand is not expected to become a bottleneck for low-carbon technologies (Simas et al., 2022).

CUMULATIVE DEMAND RELATIVE TO RESERVES AND RESOURCES

Cumulative demand from renewable energy and storage technologies could exceed reserves by 2050 (under more ambitious scenarios) (Dominish et al., 2019. See also Zhang et al., 2023 and Simas et al., 2022).

Nickel resources have more than doubled over the past 25 years (Simas et al., 2022).

Known terrestrial resources exceed projected cumulative demand (2015-2050) under the most ambitious scenarios (Teske et al., 2016).

CURRENT AND POTENTIAL RECOVERY RATE

Current recovery rates are estimated at around 35% (Hund et al., 2020) or 57% in some contexts[299] (Simas et al., 2022).

Recovery rates of 90-95% are feasible (Dominish et al., 2019; 2021; Simas et al., 2022).

IMPACT OF RECYCLING ON FUTURE DEMAND

Estimates vary:

- Considering current collection and recovery rates, recycled nickel could provide up to 47% of annual demand in 2050 (Simas et al., 2022).
- Under a circular economy scenario with lower annual mineral demand and higher collection and recovery rates, recycling could cover up to 80-90% of nickel demand by 2050 (Simas et al., 2020).
- Recycling could reduce primary demand for nickel by 35% in 2040 (Dominish et al., 2021).
- Increasing recovery and recycling at EOL to 100% by 2050 would reduce cumulative demand for lithium from energy technology by 23% (Hund et al., 2020).

SUBSTITUTABILITY

Yes - substitutable through shifts to other Li-ion sub-chemistries (e.g. LFP). Cobalt and nickel chemistries may drop out of the market by 2030 (Teske et al., 2016).

There is also scope for substitution of nickel in other products and technologies, e.g. the production of stainless steel (Simas et al., 2022).

The use of alternative compositions for EV and stationary batteries could reduce total demand for nickel by 40-50% between 2022 and 2050 (Simas et al., 2022).

Increased use of LFP batteries would see demand for nickel fall below 50% of business as usual by 2030 (Simas et al., 2022).

Unsplash / Chuttersnap

RARE EARTH ELEMENTS (REE) (NEODYMIUM & DYSPROSIUM)

MAIN CLEAN ENERGY APPLICATIONS

Energy storage, wind turbines.

ANNUAL DEMAND RELATIVE TO ANNUAL PRODUCTION

By 2030, demand is expected to exceed current annual production rates (Dominish et al., 2019).

Mean annual demand for dysprosium and neodymium is projected to increase to 309.4% and 271.4% of current production, respectively, during 2020-2050 (Wang et al., 2023).

World Bank projects annual demand from energy technologies for neodymium will represent 37% of 2018 annual production in 2050 (Hund et al., 2020).

IEA estimates the share of total REE demand driven by clean energy technologies at over 40% of total REE demand in 2040 in a scenario consistent with the goals of the Paris Agreement (IEA, 2021).

REE for wind turbines alone might require a three-fold increase in production (Wang et al, 2023).

CUMULATIVE DEMAND RELATIVE TO RESERVES AND RESOURCES

Increases in demand will be significant but no issues with long term supply are expected. Projected cumulative demand for dysprosium and neodymium by 2050 is less than 20% of reserves in all scenarios (Dominish et al, 2019).

Known terrestrial resources exceed projected cumulative demand (2015-2050) under the most ambitious scenarios (Teske et al., 2016).

CURRENT AND POTENTIAL RECOVERY RATE

Current recovery rates of REEs from permanent magnets are less than 1% (Simas et al., 2022).

Recovery rates from both EV and stationary batteries and wind power of 95% are feasible (Dominish et al., 2019) although Simas et al. (2022) cites a lower rate (60%) for dysprosium from permanent magnets.

IMPACT OF RECYCLING ON FUTURE DEMAND

While known reserves are greater than expected future demand, supply constraints may arise due to a time lag in increasing mine production rates. Increasing availability of primary and secondary REE through improved recycling and material efficiency is considered essential (Simas et al., 2022; Teske et al., 2016).

Higher collection and recovery rates could cover over half of demand for dysprosium and over 80% of demand for neodymium in 2050 (Simas et al., 2022).

Under a circular economy scenario with low REE technologies, recycling could cover up to 100% of neodymium demand in 2050 (Simas et al., 2022).

SUBSTITUTABILITY

Yes - can shift to permanent magnets for wind turbine generators and EV engines with low or no REE.

While substitution is possible, nearly all EVs currently use this technology. However, EV manufacturers are developing motor technologies that replace neodymium and dysprosium with lower cost REEs or different materials (Dominish et al., 2019).

The use of electric traction motors and wind turbine generators with low or no REEs could cut cumulative demand by 20% between 2022 and 2050 (Simas et al., 2022).

SILVER

MAIN CLEAN ENERGY APPLICATIONS

Solar PV.

ANNUAL DEMAND RELATIVE TO ANNUAL PRODUCTION

Annual demand is expected to require less than 50% of current annual production by 2050 (Dominish et al., 2019).

World Bank projects annual demand from energy technologies for silver will represent 56% of 2018 annual production in 2050 (Hund et al., 2020).

CUMULATIVE DEMAND RELATIVE TO RESERVES AND RESOURCES

Demand from renewable energy and storage technologies could reach 50% of reserves by 2050 (Dominish et al, 2019).

Known terrestrial resources exceed projected cumulative demand (2015-2050) under the most ambitious scenarios (Teske et al., 2016).

CURRENT AND POTENTIAL RECOVERY RATE

Current recovery rates are close to zero.

Recovery rates from solar PV of 81% are possible although recycling is technologically difficult (Dominish et al., 2019).

IMPACT OF RECYCLING ON FUTURE DEMAND

Material efficiency has the most potential to offset primary demand for solar PV metals due to the long lifetime of PV panels (Dominish et al., 2019).

SUBSTITUTABILITY

Silver is currently used in 95% of solar PV panels. Substitution is challenging (Dominish et al., 2019).

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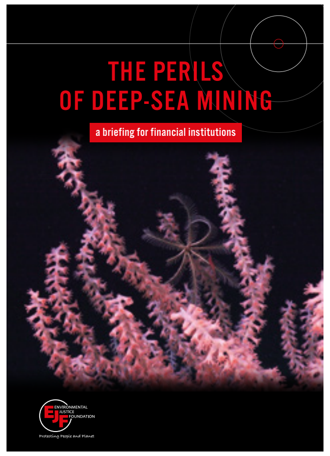

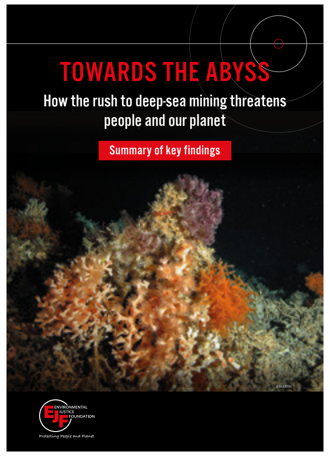

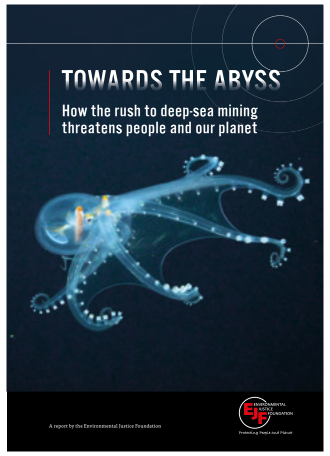

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