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Responsible minerals sourcing for renewable energy

PREPARED FOR:
Earthworks

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Cover photograph: Lithium mine at Salinas Grandes salt desert in Jujuy province, Argentina

Executive summary photograph: A creuseur, or digger, descends into a copper and cobalt mine in Kawama, Democratic Republic of Congo (Photo by Michael Robinson Chavez/The Washington Post via Getty Images)

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Executive Summary

Introduction:

The transition to a 100% renewable energy system is urgently needed to meet the goals of the Paris Climate Agreement and increase the chance of keeping global temperature rise below 1.5 degrees. Renewable energy technologies are now the most cost competitive technologies for new installations – and recent investment in new renewable energy infrastructure globally has been double that of new energy investment in fossil fuels and nuclear.

Renewable energy technologies, electric vehicles and battery storage require high volumes of environmentally sensitive materials. The supply chains for these materials and technologies need to be appropriately managed, to avoid creating new adverse social and environmental impacts along the supply chain.

This report presents the findings of an assessment of the projected mineral demand for fourteen metals used in renewable energy and storage technologies, the potential to reduce demand through efficiency and recycling, and the associated supply risks and impacts. Solar photovoltaic (PV) and wind power have been chosen for this assessment because these two technologies make up the majority of new global renewable electricity installations. Batteries have been assessed because of their importance for use in electric vehicles (EVs) and energy storage systems.

This research aims to identify the main 'hotspots' or areas of concern in the supply chain, including technologies, metals and locations, where opportunities to reduce demand and influence responsible sourcing initiatives will be most needed.

Key metals for renewable energy and storage technologies

Lithium-ion batteries: cobalt, lithium, nickel, manganese

EVs: rare earths (neodymium and dysprosium)

Solar PV: cadmium, indium, gallium, selenium, silver, tellurium

Wind power: rare earths (neodymium and dysprosium)

Aluminium and copper used in all technologies

Research overview:

The key findings presented in this report are drawn from an assessment of five important factors:

- The challenges for substitution, efficiency and recycling to offset demand
- The projected metal demand in a 100% renewable energy scenario
- The supply risks, considering concentration of producers and reserves, and the share of end-use for renewable energy technologies
- The social and environmental impacts of supply
- Current levels of industry awareness and responses

The overall key findings are outlined below, followed by the detailed findings for each of these factors.

Key findings:

Encouraging recycling and responsible sourcing are the key strategies to promote environmental stewardship and the respect of human rights in the supply chain.

The transition towards a renewable energy and transport system requires a complex mix of metals – such as copper, cobalt, nickel, rare earths, lithium and silver – many of which have only previously been mined in small amounts. Under a 100% renewable energy scenario demand for these metals could rise dramatically, and require new sources of primary and recycled metals. Recycling and responsible sourcing are fundamental to improving the sustainability of the renewable energy transition.

Recycling is the most important strategy to reduce primary demand.

Recycling of metals from end-of-life batteries was found to have the greatest opportunity to reduce primary demand for battery metals, including cobalt, lithium, nickel and manganese. Increasing efficiency or shifting away from cobalt also has a significant impact (although this may increase demand for other metals including nickel and lithium). Many electric vehicle (EV) and battery manufacturers have been proactive in establishing recycling initiatives and improving the efficiency of battery technologies. However, there is potential to improve recycling rates as not all types of metals are currently being recovered in the recycling process (e.g. lithium and manganese), or only at low rates.

Improving the efficiency of material use was found to have the greatest potential to reduce primary demand for metals for solar PV, owing to the long lifetime of these products. The industry has already made significant improvements to minimising the demand for materials, improve performance and reduce costs. However, the PV industry also needs to engage further in recycling to avoid future waste streams, and recover more metals from the process. Recycling remains a particular challenge for the solar PV industry as there is not always a strong business model.

Overall recycling is the most important strategy for the renewable energy and battery industries going forward, as the industry is already very focused on improving the efficiency of material use, which is expected to continue to improve over time.

Responsible sourcing is needed where supply cannot be met by recycled sources.

Recycling can significantly reduce primary demand, especially for batteries, however it cannot meet all demand and there is a time delay for when recycled metals become available. New mining is likely to take place to meet demand in the short term, and new mines are already under development linked to renewable energy (e.g. for cobalt, copper, lithium, rare earths, nickel). If not managed responsibly, this has the potential for new adverse environmental and social impacts.

Impacts associated with the mining of key metals used in renewable energy and storage include pollution and heavy metal contamination of water and agricultural soils, and health impacts on workers and surrounding communities. When supply cannot be met by recycled sources, engaging in responsible sourcing through verified certification schemes and due diligence of supply chains is needed to reduce potential negative social and environmental impacts.

The EV and battery industries have the most urgent need to avoid negative impacts in their supply chains.

Cobalt, lithium and rare earths are the metals of highest concern, considering their projected future demand and supply risks. Batteries for EVs are the main driver of demand for these metals, rather than stationary storage or wind power. The industry as a whole can engage further with responsible sourcing, and by doing so will encourage more mines to engage in responsible practices and certification schemes. As EV manufacturers are strong consumer facing brands, they can drive change up the supply chain and influence their suppliers upstream.

It is expected that with the renewable energy transition, renewable energy technologies will consume a growing share of these metals and in many cases may be the major driver of demand. The renewable energy transition is an opportunity to promote stewardship of both primary sources and technologies at end-of-life. This has the potential to improve the sustainability of the supply chain for these metals more broadly.

Challenges for substitution, efficiency and recycling:

Copper, lithium, silver and rare earths are the metals most challenging to reduce total demand through substitution and efficiency, and offset primary demand through recycling.

Copper is used in all technologies, and is difficult to substitute, as it is used for its high electrical conductivity. Lithium is challenging to substitute as it is used in the dominant battery technologies, as well as technologies predicted to be important in future, and currently only has limited recycling from batteries. Silver is used in 95% of PV panels, and while the industry is continuously increasing its efficiency in material use, it is not currently recycled and is technologically difficult to do so. Similarly, the rare earths neodymium and dysprosium are not currently recycled, and substitution is possible but currently nearly all EVs use this technology.

There are less challenges to reduce demand for the remaining metals as they have high recycling rates (such as aluminium, cobalt and nickel) or can more easily be substituted with other metals or other technology types (e.g. cadmium, tellurium, gallium, indium and selenium are only used in niche PV technologies). These challenges inform the projections of future metal demand.

Projected metal demand in a 100% renewable energy scenario:

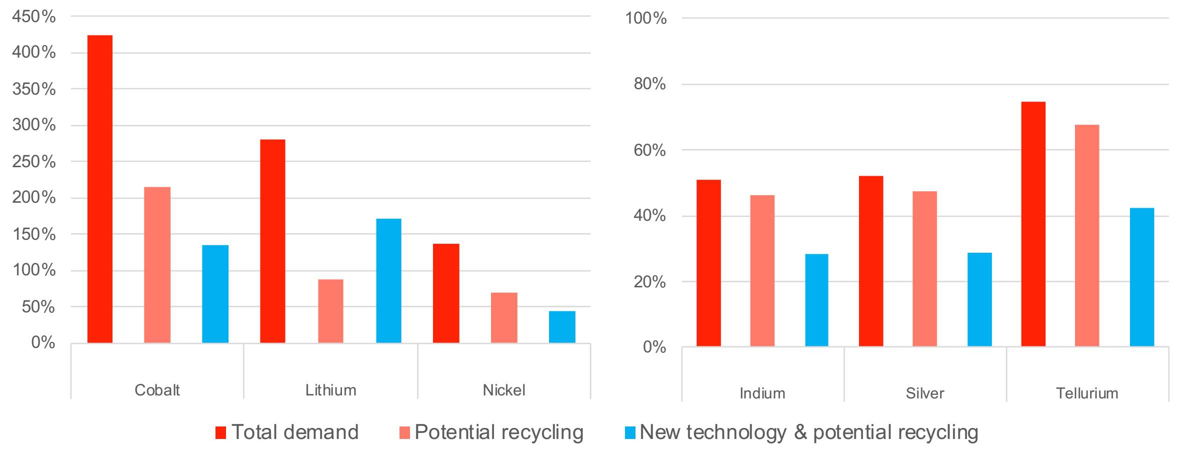
The potential metal demand from clean energy has been modelled against an ambitious scenario for a 100% renewable electricity and transport system by 2050, that limits climate change to 1.5 degrees. This scenario estimates material demand for high levels of solar PV and wind power, which provide two-thirds of electricity by 2050, as well as batteries for electric passenger cars, commercial vehicles, buses and stationary storage.

This study focuses only on the metal demand for renewable energy and storage technologies, and does not consider other demands for these metals, which may also increase or decline over time. It is also important to note that this scenario is an ambitious renewable energy scenario based on current technologies, and these results should be considered a high-demand scenario, as over time new technologies may become more efficient or new technologies may emerge. The potential to reduce primary demand is based on recycling at end-of-life of the three technologies in this study, and using recycled metals from other sources could further reduce primary demand.

- **Demand compared to reserves:**

Demand from renewable energy and storage technologies could exceed reserves for cobalt, lithium and nickel, and reach 50% of reserves for indium, silver, tellurium.[1] Primary demand can be reduced significantly, with the greatest potential to reduce demand for metals in batteries through high recycling rates, and for PV metals through materials efficiency.

Figure A: Cumulative demand from renewable energy and storage by 2050 relative to reserves in three scenarios for selected battery metals (left) and solar PV metals (right)



[1] Reserves are the estimated amount of a mineral that can be economically mined under current conditions. Reserves are a subset of resources, which are the total known amount of a mineral for which extraction may be potentially be feasible.

- **Increases in production:**

The rapid increase in demand for cobalt, lithium and rare earths is of the most concern. Demand for lithium and rare earths from lithium-ion batteries for EVs and storage exceeds current production rates by 2022 (for all uses). Demand for cobalt and nickel exceeds current production rates by around 2030.

The more rapid increase for these metals is owing to the predicted rapid electrification of the transport system and expansion of battery storage that has only begun to accelerate in the last few years, compared to established technologies of solar PV and wind.

Supply risks:

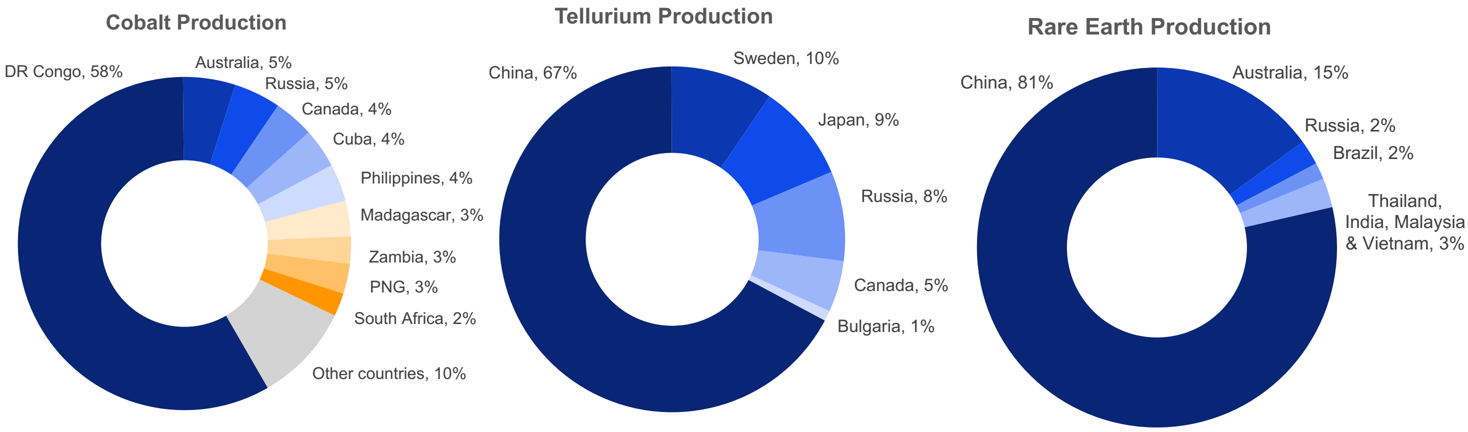
To review the risks of security of supply of the metals in renewable energy supply chains, the geographical distribution of producers and reserves, and the renewable energy share of end-use was examined. Cobalt is the metal of most concern for supply risks as it has highly concentrated production and reserves, and batteries for EVs are expected to be the main end-use of cobalt in only a few years.

The supply chains for renewable energy technologies are opaque and involve a vast number of countries and companies. Chinese companies have significant control of supply chains, including mining, processing and manufacturing, and China is also the largest end-market.

- **Concentration of production and reserves:**

The concentration of supply in a single or very few countries is a risk for manufacturers to secure ongoing supply and make the metal more vulnerable to price fluctuations. The metals for which supply is concentrated in a single country are cobalt, rare earths and tellurium (Figure B). Australia, Chile, DR Congo and South Africa have large shares of the production of metals for lithium-ion batteries and Japan, Korea, Canada and Russia have significant production levels of metals for PV, in addition to China. Although DR Congo is the major producer of cobalt and Australia of lithium, the majority of both of these metals is shipped to China for processing. China dominates the manufacturing of solar PV and lithium-ion batteries, as well as being the largest market for these technologies.

Figure B: Concentration of production



Cobalt has the highest concentration of potential supply, with nearly 50% of reserves in DR Congo. The majority of other metals are found in many regions across the globe, with Australia, Chile, Brazil and China having significant shares of many metals. Rare earths are found in many countries, but are not always economically viable to mine. Despite rare earth production being highly concentrated in China, countries in including Brazil, Vietnam and Russia, have a significant share of global reserves, but currently only a very small share of production.

- **Renewable energy share of end-use:**

The metals for which renewable energy is a significant share of end-use are cobalt, lithium, rare earths and tellurium. Lithium-ion batteries for EVs and storage are currently responsible for between 4-8% of demand for cobalt and lithium, and this could be up to 43% of demand for cobalt in 2020. For lithium this could be even higher, with EVs and storage expected to consume 50% of lithium by 2020. Permanent magnets for wind turbines and EVs are the current end market for approximately 32% of neodymium and dysprosium. Solar PV is already a large end market for tellurium (40%), gallium (17%), indium (8%) and silver (9%), and is expected to remain so.

Supply impacts:

If not managed responsibly, there are significant environmental and social impacts associated with the mining and processing of metals. These include:

- **Cobalt:** Heavy metal contamination of air, water and soil has led to severe health impacts for miners and surrounding communities in DR Congo, and the cobalt mining area is one of the top ten most polluted places in the world. Around 20% of cobalt from DR Congo is from artisanal and small-scale miners who work in dangerous conditions in hand-dug mines and there is extensive child labour. New cobalt mines are proposed in DR Congo, as well as in Australia, Canada, Indonesia, the US, Panama and Vietnam.
- **Copper:** Copper mining can lead to heavy metal contamination, as seen in Chile, China, India and Brazil, has led to environmental pollution from a major tailings dam spills in the US and there are health impacts for workers in China and Zambia.
- **Lithium:** The major concern over lithium mining is water contamination and shortages in the lithium triangle of Argentina, Bolivia and Chile, and the inadequate compensation for affected local communities.
- **Nickel:** Damage to freshwater and marine ecosystems has been observed in Canada, Russia, Australia, Philippines, Indonesia and New Caledonia.
- **Rare earths:** Rare earth processing requires large amounts of harmful chemicals and produces large volumes of solid waste, gas and wastewater. There have been impacts in China, Malaysia and historically in the US, and new mines are proposed for Canada, Greenland, Malawi, South Africa and Uganda.
- **Silver:** There has been heavy metal contamination of soil and water from recent and historical mines in the US, Mexico, Peru and Bolivia, and social conflicts in Guatemala.

Although recycling is generally environmentally preferable to mining, it needs to be done responsibly. The informal recycling of e-waste in many parts of the world is done in hazardous working conditions, that only ends up recovering a fraction of what could otherwise be recovered, and emits dangerous toxins, heavy metals and acid fumes into the surrounding environment, leading to severe illnesses.

With the growing demand for these metals from renewable energy, responsible operations are necessary to avoid negative environmental health impacts for workers and local communities, and to ensure the respect of human rights and guarantee an equitable sharing of benefits.

Industry awareness and responses:

The renewable energy, EV and battery manufacturing industries are very aware of issues around supply risks for key metals. The main concern of the industry is the ability to guarantee long-term supply of key metals at a stable price, particularly for cobalt and lithium.

The renewable energy and battery industries have made significant improvements to the efficiency of technologies, to improve performance, minimise demand for materials and reduce production costs. Current recycling infrastructure remains underdeveloped and/or not optimised for high value metal recovery, with the exception of recycling of wind turbines which relies on existing scrap recycling. The wider application of lithium-ion batteries is driving advances in recycling and the industry is very aware of the looming volumes from EV. PV recycling is demonstrated but not optimised for high value metal recovery. Policy to ensure take-back and recycling at end-of-life of batteries and solar PV will be needed if the industry does not establish effective voluntary schemes.

EV companies are beginning to engage in responsible sourcing and certification, but they are concerned about the ability to secure adequate volumes of supply from responsibly sourced mines. If the auto industry makes public commitments to responsible sourcing, it will encourage more mines to engage with responsible practices and certification schemes.

There are a large number of responsible sourcing initiatives, that promote environmental stewardship and the respect of human rights in the supply chain, most of which are voluntary and industry-led. If these initiatives are harmonised and widely adopted, it may lead to more responsible supply chains. Responsible sourcing initiatives need to ensure that they do not lead to unintended negative consequences, such as increasing poverty, by avoiding sourcing from countries with poorer governance.

Contents

Acronyms and abbreviations

ASM	Artisanal and small-scale mining
BEV	Battery electric vehicle
CCCMC	China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters
CdTe	Cadmium telluride (type of solar PV cell)
CI	Cobalt Institute
CIGS	Copper indium gallium (di)selenide (type of solar PV cell)
CO^2	Carbon dioxide
c-Si	Crystalline silicon (type of solar PV cell)
CV	Commercial vehicle (including light-duty and heavy duty vehicles)
DR Congo	Democratic Republic of Congo
DSM	Deep sea mining
EPR	Extended Producer Responsibility
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt hours
IRMA	Initiative for Responsible Mining Assurance
ISA	International Seabed Authority
LFP	Lithium iron phosphate (type of LIB)
LIB	Lithium-ion battery
Li-ion	Lithium-ion (battery)
Li-S	Lithium-sulfur (battery)
LCO	Lithium cobalt oxide (type of LIB)
LMO	Lithium manganese oxide (type of LIB)
LSM	Large-scale mining
NMC	Nickel manganese cobalt (type of LIB)
NCA	Nickel cobalt aluminium (type of LIB)
OECD	Organisation for Economic Co-operation and Development
PHEV	Plug-in hybrid electric vehicle
PNG	Papua New Guinea
PMG	Permanent magnet generator
RCI	Responsible Cobalt Initiative
RMI	Responsible Minerals Initiative
Solar PV	Solar photovoltaic
USA	United States of America
WEEE Directive	Waste Electrical & Electronic Equipment Directive (EU)

1 Introduction

The rapid increase of renewable energy and the electrification of the transport system is necessary to meet the Paris Climate Agreement and keep global temperature rise at 1.5 degrees. Renewable energy technologies are now the most cost competitive technologies for new installations – and an estimated 70% of net additions to global power capacity in 2017 was renewable, mainly solar PV and wind power.[2]

The environmental benefits of renewable energy in a future energy and transport system has been established, with positive benefits for climate mitigation and reducing pollution.[3] However, it is important to assess the material requirements of any new technology in order to minimise potentially adverse impacts that may arise, and to make sure new environmental and social impacts are not created elsewhere along the supply chain.

Renewable energy and storage technologies typically have high and diverse mineral resource requirements (Table 1). Associated with the resource requirements are potentially significant environmental and social impacts that need to be appropriately managed from resource extraction to recovery at end-of-life, in order to realise a sustainable energy system. As the renewable energy industry is comparatively new, the potential to offset the supply of primary resources with secondary resources and technological innovation is not well understood.

Table 1: Key metals required for renewable energy and storage technologies

	Batteries			Solar PV			Wind Power	
	Li-ion	**Li-S**	**EV**	**c-Si**	**CIGS**	**CdTe**	**PMG**	**Non-PMG**
Aluminium	X	X		X	X	X	X	X
Cadmium						X		
Cobalt	X							
Copper	X	X		X	X	X	X	X
Dysprosium			X				X	
Gallium					X			
Indium					X			
Lithium	X	X						
Manganese	X							
Neodymium			X				X	
Nickel	X							
Silver				X				
Selenium					X			
Tellurium						X		

[2] REN21., 2018., Renewables 2018 Global Status Report, Paris: REN21 Secretariat. Available at: http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf
[3] Hertwich, E.G. et al., 2014. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America*, 112(20), pp.6277–6282. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84929404255&partnerID=tZOtx3y1.

1.1 Project objectives

This report presents findings from an assessment of the metal requirements, supply risks and impacts for renewable energy and storage technologies. The objective of this project is to understand:

- the projected demand for minerals required for renewable energy, and the potential to offset this through secondary sources, materials efficiency, substitution or technology innovation;
- the supply risks, looking at major present and future supply regions, as well as social and environmental impacts associated with supply;
- current levels of industry awareness and responses

Through considering the above findings, this research aims to identify the main 'hotspots' or areas of concern in the supply chain, including technologies, metals and locations, where opportunities to reduce demand and influence responsible sourcing initiatives will be most needed.

1.2 Project scope

This research investigates three technologies used in renewable energy systems: battery storage systems (for transport and stationary energy storage), solar photovoltaics (PV) and wind power, and fourteen metals associated with their production as shown in Table 1.[4] For these major technologies we consider the types of technologies that are dominant today, and those that might be important in the future. For PV we consider crystalline silicon (c-Si); and, thin film technologies, copper indium gallium (di)selenide (CIGS) and cadmium telluride (CdTe). For batteries we focus on lithium-ion batteries (LIB), which encompasses a range of different types, and also look at lithium-sulfur (Li-S) as the most prospective candidate to replace LIB. For wind, we differentiate between those technologies with and without permanent magnet generators (PMG).

These technologies have been assessed because of their current and future importance for a renewable energy system. This analysis does not include other technologies that may emerge as important in future, and could influence future mineral requirements, supply risks and impacts, including hydrogen fuel cell vehicles, as their potential uptake is less certain.

Our assessment is based on interviews with industry experts and a review of literature including academic publications, market reports and investment news (Chapters 2, 4 and 5). The methodology developed to model future metal demand is described in Chapter 3.

1.3 Report overview

The research findings are presented in the following sections:

- **Metal requirements for renewable energy and storage technologies:** A review of renewable energy and storage technologies; supply chains and market trends; the metal requirements and potential to offset demand through secondary sources, materials efficiency or substitution (Chapter 2)
- **Projected metal demand for 100% renewable energy:** Projections of future demand for metals, modelled against an ambitious renewable energy scenario (Chapter 3)
- **Supply risks:** An assessment of supply risks including the concentration of production and reserves, renewable energy share of end-use and supply chain criticality (Chapter 4)
- **Environmental and social impacts of supply:** A review of known environmental, health and human rights impacts in mining (Chapter 5)
- **Industry awareness and responses:** A review of the current level of awareness of the industry of supply risks and impacts, and current initiatives to reduce demand and ensure responsible sourcing (Chapter 6)

[4] This is not a comprehensive list of all the metals that could potentially be used in clean energy technologies, but focuses on metals that are found in substantial amounts. However, this does not include steel, which is likely to be one of the largest metal requirements. This analysis also does not include material requirements for include new transmission and distribution, or vehicles themselves except for the rare earths in permanent magnets.

2 Metal requirements for renewable energy and storage technologies

Renewable energy and battery storage are complex technologies, requiring a wide range of metals. This chapter gives an overview of the key metals used for electric vehicles, battery storage, solar PV and wind power. Solar PV and wind power are the dominant renewable technologies and will most likely continue to be into the future. Solar PV accounted for more than half of newly installed renewable power capacity in 2017 and wind power approximately one-third.[5] Batteries, alongside other storage technologies, are considered to be important for future energy systems with large amounts of electricity from variable renewables. Advances in battery technologies have also enabled the electrification of the transport system, and it is electric vehicles that are driving the increased demand for batteries.[6]

These technologies are rapidly developing and evolving, and there are various sub-technologies designed for specific applications, which adds to the complexity of material use. Renewable energy and storage technologies typically have higher and more diverse metal requirements than fossil fuel power generation. However, once these technologies are manufactured and installed, there are no ongoing requirements for fuel, such as coal or natural gas.

Base metals, namely aluminium and copper, are essential for almost all renewable technologies, and are used in high amounts compared to other metals (see Tables 2 and 3). Rare earths, specifically neodymium and dysprosium, also have very high importance for renewable energy, as they are used for permanent magnets in the engine of nearly all electric vehicles (EVs) and around 20% of wind turbines. Other metals that are of high importance are cobalt, lithium, nickel and manganese used in lithium-ion batteries (LIBs), and silver for use in the majority of solar panels. There are also range of specialty metals used for thin-film solar panels for specialist applications.

The material intensity of each metal is shown in Table 2, and highlights the opportunities and challenges to offsetting demand through substitution, efficiency or recycling. The recyclability of metals *within each technology* is discussed, for example, although silver has an overall recycling rate of 30–50%[7], almost no recycling happens of silver from PV panels. A current recycling rate is given for each metal in Table 3, as well as a potential recycling rate, based on what could be technologically possible (but is not currently economic). This analysis focuses on fourteen key metals, but there are many more metals used in these technologies, and other metals may emerge as important in future. Details on the material intensity and recyclability for each technology is discussed in Sections 2.1 to 2.3.

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5 REN21., 2018., Renewables 2018 Global Status Report, Paris: REN21 Secretariat. Available at: http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf

6 Bloomberg New Energy Finance, 2018., Electric Vehicles. Available at: https://bnef.turtl.co/story/evo2018?teaser=true

7 Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F. and Sonnemann, G., 2011. *Recycling rates of metals: A status report*. United Nations Environment Programme. Available at: http://www.resourcepanel.org/file/381/download?token=he_rldvr

Table 2: Material intensity for renewable energy technologies

Technology		Aluminium	Copper	Cobalt	Lithium	Manganese	Nickel	Dysprosium	Neodymium	Silver	Gallium	Indium	Selenium	Cadmium	Tellurium
Batteries [t/GWh]	Li-ion	220	220	124	113	406	415								
	Li-S	220	220		411										
EVs [kg/vehicle]								0.083	0.695						
Solar PV [t/GW]	c-Si	32,000	4,000							4 – 20					
	CIGS	32,000	4,000								2 – 9	7 – 28	17 – 41		
	CdTe	32,000	4,000											19 – 70	17 – 60
Wind [t/GW]	PMG	560	3,000					27	198						
	Non-PMG	560	3,000												

Table 3: Recycling rates at end-of-life for renewable energy technologies

Technology		Aluminium	Copper	Cobalt	Lithium	Manganese	Nickel	Dysprosium	Neodymium	Silver	Gallium	Indium	Selenium	Cadmium	Tellurium
Batteries	Current	70%	70%	90%	0%	0%	90%								
	Potential	95%	95%	95%	95%	95%	95%								
Electric vehicles	Current							0%	0%						
	Potential							95%	95%						
Solar PV	Current	77%	34%							0%	0%	0%	0%	77%	77%
	Potential	81%	81%							81%	81%	81%	81%	81%	81%
Wind	Current	80%	90%					0%	0%						
	Potential	95%	95%					95%	95%						

2.1 Electric vehicles and battery storage

Technology overview and markets

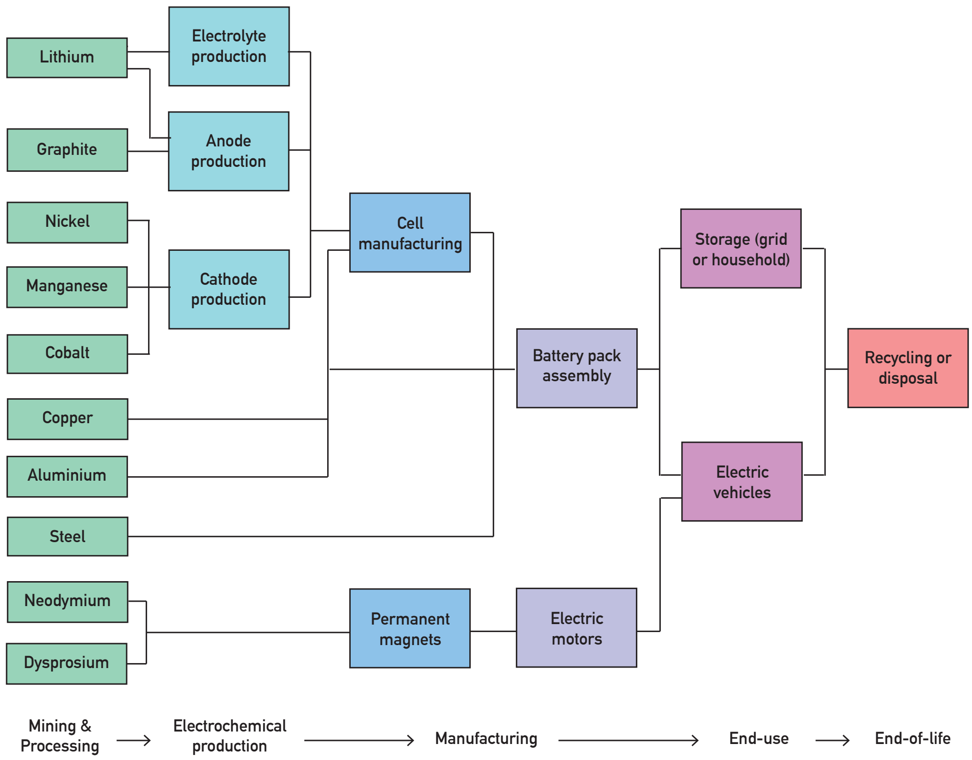
Lithium-ion batteries power almost all electric vehicles in the market today as well as most stationary energy storage applications.[8] At this very early stage of adoption, EVs represent less than 1% of the global passenger vehicle market with cumulative sales reaching about two million in 2016.[9] Most of this early adoption has been supported by government incentives in China and Europe.[10] However, major future expansion of the EV market is anticipated as part of a broad decarbonisation strategy, and to mitigate urban air pollution.[11] Sales of EVs reached a record 1.1 million vehicles worldwide in 2017.[12] Most major auto-manufacturers are now producing EVs, offering battery electric vehicles (BEV) and/or a plug-in hybrid electric vehicles (PHEV). Several auto-manufacturers (including General Motors and Toyota) have announced plans to sell only EV or hydrogen fuel cell vehicles in the near future, and several countries plan to phase-out or ban sales of petrol and diesel powered cars.[13] The main battery cell manufacturers are based in China, Korea, Japan and the US, with a small amount of manufacturing in Europe, and cathode materials are mainly produced in China.[14]

The electrification of the transport system is also underway for electric buses, commercial vehicles and 2-wheelers. Electric buses are now in use in Europe and China, particularly for short inner-city trips, and this is expected to continue growing.[15] The electrification of commercial vehicles will be important to reduce fossil fuel consumption in the transport sector, as trucks make up around 20% of fuel demand in the transport sector, although they only represent 5% of the vehicle stock.[16] Electric Light Duty Vehicles are now emerging on the market[17]. However, electric Heavy Duty Vehicles for long-distance freight will take longer to become economically viable, owing to the large size of and cost of battery required to power a large vehicle over long distances[18], and hydrogen fuel cells may emerge as a more suitable technology.[19] There are already around 200 million electric bicycles, scooters and motorbikes in China, following a ban on petrol scooters in many cities, and Europe is the second biggest market.[20]

The market for battery storage systems is also growing, however in most markets it is secondary to EVs. Batteries can be used at either utility scale or behind-the-meter, to ensure energy system adequacy and security. LIBs are commonly used for storage applications, as the very high round-trip efficiency of charge-discharge makes them attractive compared to most alternatives. However, there are various other battery types which are suitable, as most storage applications do not require the high energy density of LIBs. Lead-acid batteries have traditionally been used for off-grid storage applications, and may continue to do so in some regions due to their low cost. Sodium and flow batteries are the most likely battery technologies to gain market share from LIB for storage applications in the future. There are also a range of other technologies that can help with storage needs including pumped hydro, concentrated solar power with thermal storage and hydrogen.

[8] Energy Insights by McKinsey, 2018. Metal mining constraints on the electric mobility horizon. Available at: https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/
[9] Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. Nature Energy, 3(4), p.279.
[10] For example the European Automobile Manufacturers Association (ACEA) provides an 'Overview on Tax Incentives for EVs in EU' that is available at: https://www.acea.be/uploads/publications/EV_incentives_overview_2018.pdf
[11] IEA, 2017, Energy Technology Perspectives 2017. Available at: http://www.iea.org/etp2017 : IEA, 2017, Global EV Outlook 2017: Two Million and Counting. Available at: https://www.iea.org/publications/freepublications/publication/global-ev- outlook-2017.html
[12] Bloomberg New Energy Finance, 2018., Electric Vehicles. Available at: https://bnef.turtl.co/story/evo2018?teaser=true
[13] Eisenstein, P. 2017, NBC News, 3 October 2017. Available at: https://www.nbcnews.com/business/autos/gm-going-all-electric-will-ditch-gas-diesel-powered-cars-n806806
[14] Major companies include Panasonic, BYD, CATL, LG Chem and Samsung SDI.
[15] Bloomberg New Energy Finance, 2018., Electric Buses in Cities. Available at: http://www.ourenergypolicy.org/wp-content/uploads/2018/04/1726_BNEF_C40_Electric_buses_in_cities_FINAL_APPROVED_2.original.pdf
[16] Energy Insights by McKinsey, 2017. Available at: https://www.mckinseyenergyinsights.com/insights/new-reality-electric-trucks-and-their-implications-on-energy-demand/
[17] Sripad, S. and Viswanathan, V., 2017. Evaluation of current, future, and beyond li-ion batteries for the electrification of light commercial vehicles: Challenges and opportunities. *Journal of The Electrochemical Society*, 164(11), pp.E3635-E3646.
[18] Sripad, S. and Viswanathan, V., 2017. Performance metrics required of next-generation batteries to make a practical electric semi truck. *ACS Energy Letters*, 2(7), pp.1669-1673.
[19] Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. Nature Energy, 3(4), p.279.
[20] Fishman, E. and Cherry, C., 2016. E-bikes in the Mainstream: Reviewing a Decade of Research. *Transport Reviews*, 36(1), pp.72-91.

Figure 1: Overview of lithium-ion battery supply chain



Material requirements

Lithium-ion batteries are made of two electrodes (anode and cathode), current collectors, a separator, electrolyte, container and sealing parts. The anode is typically made of graphite with a copper foil current collector. The cathode is typically a layered transition metal oxide with an aluminium foil current collector. In between the electrodes is a porous separator and electrolyte. All of these components are typically housed in an aluminium container. LIBs are generally referred to by the material content of the cathode that accounts for 90% of the material value and about 25% of the total weight.[22] A simplified overview of the lithium-ion battery supply chain, including key materials (for the NMC chemistry) and sub-components, is shown in Figure 1.

The size and chemistry of the battery has the biggest impact on the material requirement. Since commercialisation of LIB technology in the 1990s a range of different types ('chemistries') have been developed for different applications, named by the metals in the cathode. The most common LIB types for EV applications are Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate (LFP), Nickel Cobalt Aluminium (NCA) and Lithium Manganese Oxide (LMO).[23] In most markets, NMC is the most common battery type for passenger vehicles, followed by NCA, with a small share for LMO. However, in China LFP has been the dominant chemistry. Electric buses have traditionally used LFP batteries[24] and lead-acid batteries are the most common for 2-wheelers in China and South East Asia, however LIBs are projected to become more common as the costs reduce.[25] For energy storage, NMC and NCA are most common of the lithium-ion chemistries. Rare earth permanent magnets (based on neodymium and dysprosium) are common in most electric vehicles, enabling high performance motors.[27]

[22] Gratz, E., Sa, Q., Apelian, D. and Wang, Y., 2014. A closed loop process for recycling spent lithium ion batteries. *Journal of Power Sources*, 262, pp.255-262.
[23] Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, 3, p.18013
[24] Bloomberg New Energy Finance, 2018., Electric Buses in Cities. Available at: http://www.ourenergypolicy.org/wp-content/uploads/2018/04/1726_BNEF_C40_Electric_buses_in_cities_FINAL_APPROVED_2.original.pdf
[25] Yan, X., He, J., King, M., Hang, W. and Zhou, B., 2018. Electric bicycle cost calculation models and analysis based on the social perspective in China. *Environmental Science and Pollution Research*, pp.1-13.
[27] Values from: Hoenderdaal, S., Espinoza, L.T., Marscheider-Weidemann, F. and Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies?. *Energy,* 49, pp.344-355.

Potential to offset demand

Material efficiency

The range of future battery types, and hence material inputs, are expected to be very different in the future. There is already a focus on reducing the amount of cobalt within LIBs with a shift towards 'NMC811' that contains Nickel Manganese Cobalt in a ratio of 8:1:1 in the cathode, compared to the most common chemistry 'NMC111' that containers equal parts of each metal.[28] This will see an increase in demand nickel and decrease in cobalt and manganese, and has implications for future recycling because the high value of the cobalt is an important economic driver.

At the same time many companies are aiming to reduce cobalt use, Chinese battery manufacturers are shifting towards NMC batteries, away from LFP batteries. This shift is driven by the superior performance of NMC chemistry and because of government policy introduced in 2016 that sets a minimum energy density for batteries that cannot be met by LFP. Therefore, it is likely NMC chemistries will continue to be the preferred technology in the short term.[29]

Emerging battery technologies not yet on the market may also affect material requirements in the future, and reduce demand for the more valuable metals. A recent evaluation of the range of available and emerging battery technologies argued that the critical factors for scale-up are reducing cost, overcoming limited capacity that is associated with 'range anxiety', and improving safety.[31] A continued shift away from the dominant cobalt-rich LIB types and a broader shift away from LIB technology is predicted to meet future requirements for three important market sectors: long-range, high-utilisation (freight and public transport), and the low-cost market. Lithium-sulfur (Li-S) is considered the most prospective candidate to replace the currently dominant LIB types.[32]

The size of the battery presents the most simple way to reduce the material consumption of batteries for electric vehicles. The battery size can vary hugely, with the batteries in passenger vehicles ranging between 15 and 100kWh.[33] There is a trend for luxury auto-manufacturers to increase the size of the battery to extend the range, however other manufacturers are focused on more affordable vehicles with smaller sized batteries. Other motor technologies which replace rare earths with lower cost materials are under development and already used in some vehicles, but rare earth magnets are expected to remain the standard in electric vehicles for the foreseeable future.[34]

Recycling

The collection efficiency of batteries at end-of-life is likely to be very high, as although the recycling process is not mature, the collection channels already exist (i.e. auto dealerships). Battery collection is required by European law, and in certain jurisdictions where regulations do not apply manufactures already offer cash rebates to incentivise battery take-back.[35]

Lithium-ion batteries can be recycled through two main processes, pyro-metallurgical or hydro-metallurgical, and there are various process routes combining these key processes that are under development. Current recycling processes prioritise the recovery of valuable cobalt and nickel while the less valuable metals including lithium and manganese are not usually recovered, but may be down-cycled for lower value applications.[37] Although lithium and manganese are 'technically recyclable' they are hard to separate from the other metals without the use of expensive organic reagents for solvent extraction.[38] As demand increases for these metals the economic drive to recover these may justify recovery.

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[28] Energy Insights by McKinsey, 2018. Metal mining constraints on the electric mobility horizon. Available at: https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/

[29] Castellano, R., 2017. How to minimise Tesla's cobalt supply chain risk, Seeking Alpha. Available at: https://seekingalpha.com/article/4113417-minimize-teslas-cobalt-supply-chain-risk

[31] Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. Nature Energy, 3(4), p.279.

[32] LI-S is an emerging rechargeable battery with a sulfur cathode and a lithium metal anode. The potential future importance of this emerging rechargeable battery type has also been observed by several studies.

[33] Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, 3, p.18013

[34] Widmer, J.D., Martin, R. and Kimiabeigi, M., 2015. Electric vehicle traction motors without rare earth magnets. *Sustainable Materials and Technologies*, 3, pp.7-13.

[35] For example: https://www.toyota.com.au/hybrid/battery-recycling

[37] King S, Boxall NJ, Bhatt AI., 2018, Australian Status and Opportunities for Lithium Battery Recycling. CSIRO, Australia

[38] Gratz, E., Sa, Q., Apelian, D. and Wang, Y., 2014. A closed loop process for recycling spent lithium ion batteries. Journal of Power Sources, 262, pp.255-262

An overview of current and potential recycling rates used for this study is given in . Recycling rates were determined based on a collection efficiency and a recovery efficiency for each metal in the recycling process. The current recycling rate for cobalt and nickel is assumed to be 90%[39], assuming a collection efficiency of 100% for all batteries. It is assumed around 10% of lithium is currently recycled, considering that lithium recovery is possible based on hydro-metallurgical processing routes that are utilised by several global recyclers (including Umicore, Recupyl and Batrec). However, pyrometallurgical processing routes where lithium recovery is typically not recovered account for most of the current global recycling capacity.[40] Copper and aluminium can also be recovered during mechanical pre-processing at rates of approximately 70%, however recyclers have reported higher recovery rates.[41]

We estimate a potential future recycling rate of 95% recovery for all metals noting that 100% recovery has been reported in the laboratory[42] and a number of companies are promoting 100% recovery on the basis of 'proof of concept' pilot trials.[43] Nonetheless, some losses are inevitable, for instance the generation of metal dust during pre-processing.[44] Neodymium and dysprosium are currently not recycled, although up to 95% is assumed to be technologically possible.[45]

Table 4: Battery and EV material intensity and recycling rates

Materials	Aluminium	Copper	Lithium	Cobalt	Nickel	Manganese	Dysprosium	Neodymium
Current materials intensity [t/GWh]	220	220	113	124	415	406	0.083 kg/ vehicle	0.695 kg/ vehicle
Future technology [t/GWh]	220	220	411	0	0	0	0.083 kg/ vehicle	0.695 kg/ vehicle
Current recycling rate [%]	70%	70%	0%	90%	90%	0%	0%	0%
Potential recycling rate [%]	95%	95%	95%	95%	95%	95%	95%	95%

Note: Current materials intensity based on an assumed market share of a range of LIB technologies: NMC (60%), LMO (20%), NCA (15%), and LFP (5%)[46]. Future technology based on introduction of Li-S batteries.[47] Current recycling rate based on a collection efficiency of 100% and recovery rates from various studies. Potential recycling rate based on assumption of 95%.

Reuse of EV batteries for stationary storage

The reuse of LIBs used for EVs is emerging as an important end-of-‘first’-life option. The reuse of batteries extends the useful life of a battery and can offset demand for new materials with minimal additional energy requirements compared to recycling. Owing to the performance requirements of batteries for EV applications, LIBs may be considered to have reached end-of-life when they approach 80% of their original capacity; however, these batteries may remain useful for alternative applications, such as stationary storage.[48] Many of the major manufacturers are exploring stationary energy storage applications, for example Renault in partnership with Powervault are trialling the reuse of EV batteries for home storage systems.[49] If reuse becomes an important option for end-of-life EV batteries, new policies may be needed to assure consumers that reused batteries are safe and reliable and to fairly allocate responsibilities for management at the end-of-second-life.

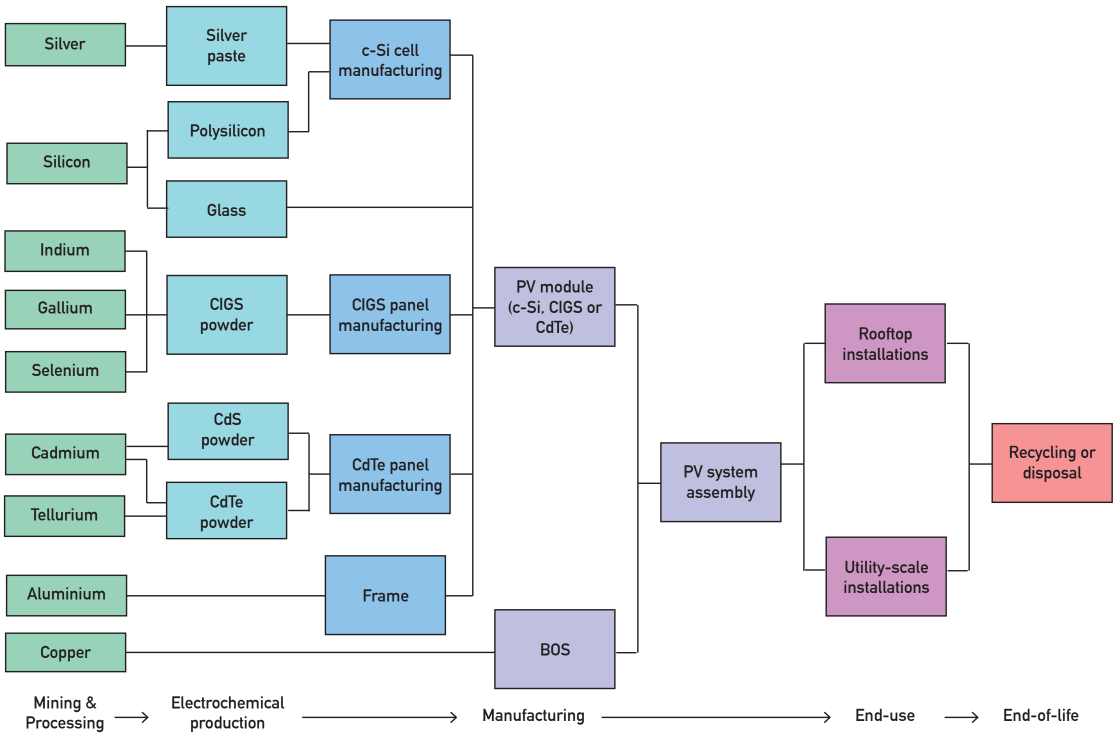
[39] Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegn, H. and Rutz, M., 2012. Development of a recycling process for Li-ion batteries. *Journal of power sources*, 207, pp.173-182.
[40] King S, Boxall NJ, Bhatt AI (2018) Australian Status and Opportunities for Lithium Battery Recycling. CSIRO, Australia
[41] Assumption based on interviews; Australian recycler Envirostream have reported recovery rates of 100% of Cu and Al
[42] Gratz, E., Sa, Q., Apelian, D. and Wang, Y., 2014. A closed loop process for recycling spent lithium ion batteries. Journal of Power Sources, 262, pp.255-262.
[43] See: https://americanmanganeseinc.com/investor-info-3/investment-proposition/
[44] Pers comms Boxall, N. CSIRO, Australia
[45] Fraunhofer Institute, 2018, Recycling of rare earth magnets. Available at: https://www.materials.fraunhofer.de/en/business-areas/energy_and_environment/recycling-of-rare-eart-magnets.html
[46] Values from: Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, *3*, p.18013
[47] Simon, B., Ziemann, S. and Weil, M., 2015. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: Focus on Europe. *Resources, Conservation and Recycling*, 104, pp.300-310
[48] King S, Boxall NJ, Bhatt AI (2018) Australian Status and Opportunities for Lithium Battery Recycling. CSIRO, Australia
[49] See: https://media.group.renault.com/global/en-gb/media/pressreleases/92203/renault-et-powervault-donnent-une-seconde-vie-aux-batteries-des-vehicules-electriques1

2.2 Solar PV

Technology overview and markets

There are two main types of PV panels used today, crystalline silicon (c-Si) and thin film technologies. Crystalline silicon technology dominates the global market with more than 95% of market share.[50] Thin film technologies including copper indium gallium (di)selenide (CIGS) and cadmium telluride (CdTe) make up the remainder of the market, and are used in more specialist applications. A simplified diagram of the PV supply chain, including key materials and sub-components, is shown in Figure 2.

Figure 2: Overview of solar PV supply chain



The manufacturing of c-Si PV panels is concentrated in a small number of countries, and is led by China where the size of the industry far exceeds that of all other countries combined. China is the world's largest producer and exporter of end-products (PV modules) and sub-components (cells), followed by Taiwan and Japan. The United States, Germany and South Korea are the largest exporters of polysilicon, mainly to China and Japan, however China is still the largest producer. Silver pastes are produced in China, Japan, South Korea and Taiwan. The largest end markets are China, United States, Japan and India[51].

Material requirements

A typical crystalline silicon PV panel contains about 76% glass (panel surface), 10% polymer (encapsulant and back-sheet foil), 8% aluminium (frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (e.g. tin and lead).

[50] Fraunhofer Institute for Solar Energy Systems, 2018. Photovoltaics report. Available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf
[51] Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: https://www.nrel.gov/docs/fy17osti/65619.pdf

Thin film technologies require less material overall compared to crystalline silicon. For CdTe panels the glass content is 96-97%, 3-4% polymer and less than 1% for semiconductor material (CdTe) and other metals (e.g. nickel, zinc, tin). CIGS contain about 88-89% glass, 7% aluminium, 4% polymer with less than 1% semiconductor material (indium, gallium, selenium) and other metals (e.g. copper).[52]

Potential to offset demand

Material efficiency

The material use in PV panels has decreased significantly since the commercialisation of the technology, particularly for silver and polysilicon that are the most expensive materials in c-Si panels. This reduction of silver is expected to continue, and could halve in the next decade.[56] The future substitution of silver with copper, a less expensive material, is envisioned by the industry. However, there are no technologies currently on the market, and the International Technology Roadmap for Photovoltaic (ITRPV) expects that copper-based c-Si technologies will be introduced to mass-production but will reach less than <15% of the market by 2028.[57]

Recycling

Recycling of PV panels is not a mature industry owing to the typical long-life expectancy of most modules (approximately 30 years). The volumes of end-of-life panels are generally too low for recycling to be economically favourable at present, however there are recycling schemes in place in some jurisdictions.[58]

Most current recycling of PV panels focuses on recycling glass, aluminium and copper, and the small amounts of other metals are not recovered. Even silver is not usually recovered, although it is the most valuable metal in a typical panel representing nearly 50% of the material value.[59] Presently PV panels are recycled in existing recycling plants (for glass and scrap metal) using manual and mechanical methods. These processes can achieve high recovery of glass and aluminium (> 90%),[60] and around 40% of copper.[61]

The other metal components predominantly end up in the glass and encapsulant (polymer e.g. ethylene-vinyl-acetate) fractions following mechanical processing. The main technical challenge is the removal of the encapsulant that is designed to last for decades in harsh environments without losing its functional properties.[62] Thus, while ‘technically recyclable’, recovering the small amounts of valuable (e.g. silver, copper), scarce (e.g. indium, tellurium), or most hazardous materials (e.g. cadmium, lead, selenium) requires additional thermal treatment, or the use of organic solvents. Cadmium and tellurium from CdTe panels are able to be recovered at around 90% efficiency, and the largest manufacturer First Solar has a recycling program in place.[63]

In order to estimate an overall recycling rate for each metal for this study, we have multiplied the recovery efficiency discussed above by a collection efficiency. We have assumed a current collection efficiency of 85% for all panels, based on the target from the EU.[64] This is an estimate, noting that the location and type of installation will likely have a major impact on collection efficiency. For example, the collection of small rooftop PV systems, or systems in remote locations, will be more expensive to collect and transport to recycling facilities compared to large utility-scale PV. The assumed material intensity and recycling rates are shown in .

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[52] These are average values drawn from a range of published sources as summarised by Weckend, S.;Wade, A.; Heath, G. End-of-Life Management Solar Photovoltaic Panels; International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems: Paris, France, 20

[56] Ibid

[57] The International Technology Roadmap for Photovoltaics (ITRPV) is a public resource made available by VDMA that is a major industry group representing PV (c-Si) manufacturers and suppliers, available at: http://www.itrpv.net/Home/

[58] Weckend, S.; Wade, A.; Heath, G. End-of-Life Management Solar Photovoltaic Panels; International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems: Paris, France, 20

[59] Ibid

[60] Assuming aluminium from frame that is manually removed

[61] Based on LCA study: Latunussa, C.E., Ardente, F., Blengini, G.A. and Mancini, L., 2016. Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Solar Energy Materials and Solar Cells, 156, pp.101-111

[62] Weckend, S.; Wade, A.; Heath, G. End-of-Life Management Solar Photovoltaic Panels; International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems: Paris, France, 20

[63] Based on conference presentation from FirstSolar that suggests 95% recovery of semiconductor material in metals rich filter cake based on wet process

[64] More details available here: http://ec.europa.eu/environment/waste/weee/index_en.htm

Table 5: Solar PV material intensity and recycling rates

	All PV		c-Si	CIGS			CdTe	
Materials	**Aluminium**	**Copper**	**Silver**	**Gallium**	**Indium**	**Selenium**	**Cadmium**	**Tellurium**
Current materials intensity [t/GW]	32,000	4,000	20	9	28	41	70	60
Improved materials intensity [t/GW]	32,000	4,000	4	2	7	17	19	17
Current recycling rate [%]	77%	34%	0%	0%	0%	0%	77%	77%
Potential recycling rate [%]	81%	81%	81%	81%	81%	81%	81%	81%

Note: Aluminium[65] and copper[66] are used in all three technologies and the intensity is assumed to remain the same as these are not a focus for efficiency. Data for the current materials intensity of silver is from a survey of the PV industry which also projects improved materials intensity.[67] Data for the remaining metals is from Kavlak et al, and gives a high value for current materials intensity and the lowest value for improved materials intensity. These are theoretical figures calculated by varying the assumed thickness of the cells, the module efficiencies and material losses during manufacturing.[68] Current recycling rate based on a collection efficiency of 85% and recovery rates from various studies. Potential recycling rate based on assumption of 95% recovery efficiency and when considering the 85% collection efficiency, this give an overall potential recycling rate of 81%.

[65] Bödeker, J.M.; Bauer, M.; Pehnt, M. Aluminium and Renewable Energy Systems—Prospects for the Sustainable Generation of Electricity and Heat; Institut für Energie und Umweltforschung Heidelberg GmbH: Heidelberg, Germany, 2010

[66] The Warren Centre. The Copper Technology Roadmap 2030 Asia's Growing Appetite for Copper

[67] International Technology Roadmap for Photovoltaic (ITRPV), 2018, International Technology Roadmap for Photovoltaic Results 2017, Ninth Edition. Available at: http://www.itrpv.net/Reports/Downloads/

[68] Kavlak, G., McNerney, J., Jaffe, R.L. and Trancik, J.E., 2015. Metal production requirements for rapid photovoltaics deployment. *Energy & Environmental Science*, 8(6), pp.1651-1659. We have used the high values for gallium and indium and the medium values for selenium, cadmium and tellurium, as these are closest to the averages given in other studies.

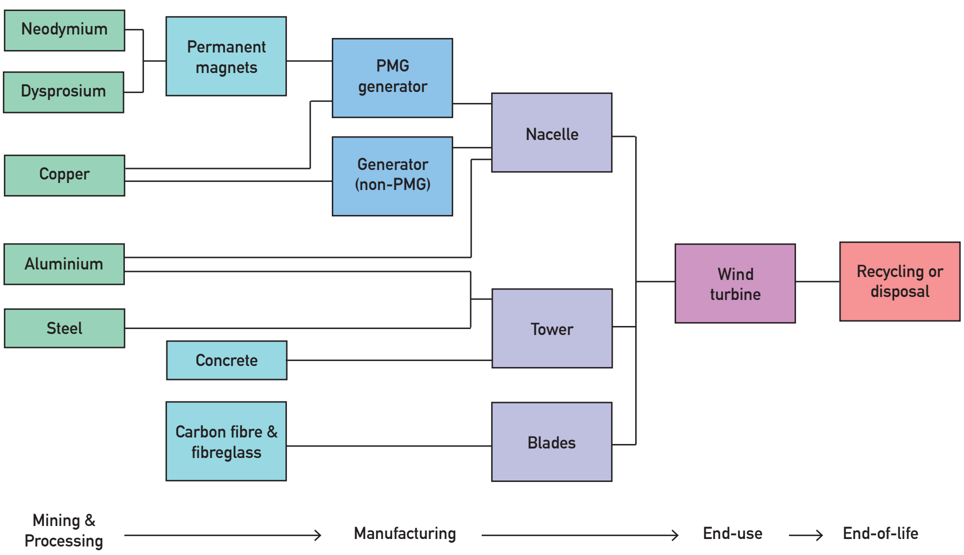
2.3 Wind

Technology overview

Wind power is the most established new-generation renewable technology and most competitively priced. The installed capacity exceeds all other non-hydro renewables, reaching 539 GW globally in 2017.[69] The valuable wind resource at sea is now being harnessed by offshore wind farms with foundations embedded in the ocean floor and new floating wind turbines. However, owing to the higher costs of wind turbines off-shore, on-shore technology is expected to remain the dominant application in the near to midterm.

Until the early 2000s, the manufacture of wind turbine components mostly occurred in the EU and then transported around the world. More recently manufacturing is happening in dozens of different locations serving local and regional markets. This shift corresponds with a significant increase in size of wind turbine components, leading to transport cost savings. For example, there are 5 of 10 large wind turbine manufacturers located in China meeting Chinese demand and these manufacturers are also exporting sub-components to the global wind industry.[70]

Figure 3: Overview of wind power supply chain



Material requirements

Although a range of wind turbine technologies exist for different conditions, the predominant design is a horizontal-axis turbine with three blades that rotate upwind around a horizontal axis on a 80 to 120m tower. The major raw materials required for the manufacture of wind turbines are bulk commodities: steel, copper, aluminium, concrete and carbon. The steel structural components account for about 80% of the total weight of the turbine.

Some turbine generator designs use direct-drive permanent magnet generators (PMG) that contain rare earth metals, neodymium and dysprosium (Figure 3). The development of direct-drive PMGs by major producers (e.g. Siemens and General Electric) simplifies the design by eliminating the gearbox and this is particularly attractive for off-shore applications because it minimises maintenance requirements.[71] It is estimated that about 20% of all installed wind turbines (including on-shore and off-shore) use rare earth permanent magnets.[72]

[69] Global Wind Energy Council, 2018, Global Wind Report. Available at: http://gwec.net/global-figures/wind-energy-global-status/
[70] Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: https://www.nrel.gov/docs/fy17osti/65619.pdf
[71] Zimmermann, T., Rehberger, M. and Gößling-Reisemann, S., 2013. Material flows resulting from large scale deployment of wind energyin Germany.Resources, 2(3), pp.303-334.
[72] Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: https://www.nrel.gov/docs/fy17osti/65619.pdf

Potential to offset demand

Material efficiency

The material use of bulk metals is not expected to change significantly. As the most established next-generation renewable technology, material use for wind turbines is already very efficient, and advances in turbine technology have enabled capacities up to 7MW in a single machine.

Off-shore technology tends to have higher material requirements, mostly bulk materials for foundations and extended towers or for transmission, so an increase in off-shore turbines could increase metal requirements. As noted above, only about 20% of all installed wind turbines use permanent magnet generators with rare earths. This limited share is likely linked to supply constraints, with China currently manufacturing about 90% of all rare earth magnets while consuming about 75% of the global supply. It is speculated that increases in the use of rare earth magnet generators could occur if new rare earth mines and processing facilities are established.[76]

Future innovations that may lead to material savings, for example lighter towers and blades enabled by the use of carbon fibre or other composites, are possible but have not been considered in this analysis.

Recycling

Recycling of the bulk materials (steel, aluminium, copper) used in wind turbines is well established, with high recycling rates, as shown in .[77] These materials account for about 80-95% of the materials used in wind turbines by weight. There is currently no recycling of dysprosium or neodymium from permanent magnets, but this could be technologically possible, and making it economically viable is the focus of significant research and development at the laboratory scale.[78]

Table 6: Wind power material intensity and recycling rates

Materials	Aluminium	Copper	Dysprosium	Neodymium
Current materials intensity [t/GW]	560	3,000	0	0
PMG materials intensity [t/GW]	560	3,000	27	198
Current recycling rate [%]	80%	95%	0%	0%
Potential recycling rate [%]	95%	95%	95%	95%

Note: The assumed material intensity for aluminium[79], copper[80], dysprosium and neodymium[81] are based on on-shore technologies. Current recycling rate based on a collection efficiency of 100% and recovery rates from various studies. Potential recycling rate based on assumption of 95%.

[76] Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: https://www.nrel.gov/docs/fy17osti/65619.pdf
[77] Zimmermann, T., Rehberger, M. and Gößling-Reisemann, S., 2013. Material flows resulting from large scale deployment of wind energy in Germany. *Resources*, 2(3), pp.303-334.
[78] Fraunhofer Institute, 2018, Recycling of rare earth magnets. Available at: https://www.materials.fraunhofer.de/en/business-areas/energy_and_environment/recycling-of-rare-eart-magnets.html
[79] Average of values from three studies: Bödeker, J.M.; Bauer, M.; Pehnt, M. Aluminium and Renewable Energy Systems—Prospects for the Sustainable Generation of Electricity and Heat; Institut für Energie und Umweltforschung Heidelberg GmbH: Heidelberg, Germany, 2010; Kleijn, R. and Van der Voet, E., 2010. Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. *Renewable and Sustainable Energy Reviews*, 14(9), pp.2784-2795; Elshkaki, A. and Graedel, T.E., 2013. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *Journal of Cleaner Production*, 59, pp.260-273.
[80] Value from: Wilburn, D.R. Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030. 2011. Available online: http://pubs.usgs.gov/sir/2011/5036
[81] Value from: Hoenderdaal, S., Espinoza, L.T., Marscheider-Weidemann, F. and Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies?. *Energy*, 49, pp.344-355.

2.4 Summary of challenges to reducing demand

Copper, lithium, silver and rare earths are the metals most challenging to reduce total demand through substitution and efficiency, and offset primary demand through recycling.

Copper is used in all technologies, and is difficult to substitute, as it is used for its high electrical conductivity. It is challenging to reduce demand for lithium as it is used in the dominant lithium-ion battery technologies, and currently only has limited recycling. Lithium is also used in Li-S batteries which are a promising future technology for EVs, but other technologies which don't use lithium (such as sodium) could be used for storage in future. Silver is used in 95% of PV panels, and while the industry is continuously increasing its efficiency in material use, it is not currently recycled and is technologically difficult to do so. Similarly, the rare earths neodymium and dysprosium are not currently recycled, and substitution is possible but currently nearly all EVs use this technology.

Aluminium is also very important as it is used in all technologies, as well as cobalt and nickel which are used in main Lithium-ion battery chemistries. However, these metals can be substituted (with some loss of performance) and currently have high recycling rates. The remaining metals are of less concern as they can more easily be substituted with other metals or other technology types (e.g. cadmium, tellurium, gallium, indium and selenium are only used in niche PV technologies and can be avoided by switching to alternative panel types in many cases). A summary of the challenges to offsetting metal demand is shown in Table 7.[82]

Table 7: Summary of challenges to reducing demand

	Importance to renewable energy	Materials efficiency or substitution	Current recyclability
Aluminium	High – used for wind, PV & batteries	With some loss of performance (steel, plastic)	~70-80% recycled
Cadmium	Low – CdTe small share of PV market	Efficiency increasing, can shift to other PV types	~77% recycled
Cobalt	Medium – Li-ion dominant battery technology	Efficiency increasing, can shift with loss of performance (LFP)	90% recycled
Copper	High – used for wind, PV & batteries	Difficult to substitute in most applications	~34-95% recycled
Dysprosium	High – used for wind & batteries	Can shift to other magnet or motor types, or non-PMG wind	Not currently recycled
Gallium	Low – CIGS small share of PV market	Efficiency increasing, can shift to other PV types	Not currently recycled
Indium	Low – CIGS small share of PV market	Efficiency increasing, can shift to other PV types except flexible	Not currently recycled
Lithium	Medium – Li-ion dominant battery technology	Efficiency increasing, but used for all Li-ion and Li-S	~10% recycled
Manganese	Medium – Li-ion dominant battery technology	Efficiency increasing, can shift to other battery types (LFP, NCA)	Very limited recycling
Neodymium	High – used for wind & batteries	Can shift to other magnet or motor types, or non-PMG wind	Not currently recycled
Nickel	Medium – Li-ion dominant battery technology	Efficiency increasing, can shift with loss of performance (LFP)	90% recycled
Silver	Medium – cSi large share of PV market	Efficiency increasing, copper possible but not commercialised	Not currently recycled
Selenium	Low – CIGS small share of PV market	Efficiency increasing, can shift to other PV types	Not currently recycled
Tellurium	Low – CdTe small share of PV market	Efficiency increasing, can shift to other PV types	~77% recycled

[82] A 'traffic light' rating scheme is used to give an indication of the potential or challenges to offset demand for each metals. For importance to clean energy, red represents metals that are of high importance (used in multiple technologies and therefore harder to replace), orange represents medium importance (used in the dominant sub-technology) and yellow is for the least importance (used in less dominant sub-technology). For materials efficiency or substitution, red represents the metals most difficult to reduce or substitute (either metals in the technology or between sub-technologies), orange can be substituted but with some loss of performance and yellow are the most suitable for efficiency or substitution. Lastly recyclability is rated based on current rates of recycling, from red (not currently recycled), orange (some recycling) and yellow (currently recycled).

3 Projected metal demand for 100% renewable energy

This chapter presents scenarios for the demand for metals in a future renewable energy system. The aim of this analysis is to determine projected total demand and production rates, and how primary demand could be offset through changes in technology or recycling rates. This is useful for understanding which metals may present as bottlenecks to the deployment of renewable energy technologies, where new primary or secondary supply will be needed, and which strategies have the greatest impact on reducing primary demand for each metal and technology.

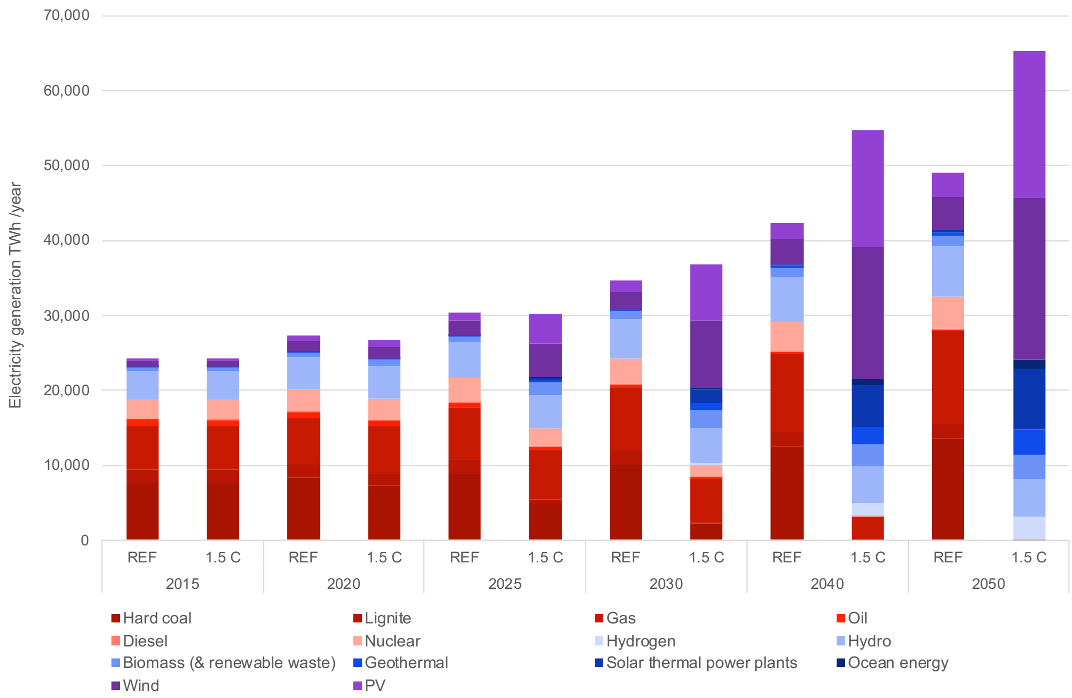
3.1 Future energy and resource scenarios

The future demand for metals has been modelled against an ambitious scenario for a 100% renewable energy and transport system by 2050. This energy scenario was developed by the Institute for Sustainable Futures (ISF) at the University of Technology Sydney (UTS), in partnership with the German Aerospace Centre (DLR), Institute for Engineering Thermodynamics, Department of Systems Analysis and Technology Assessment (STB).[83]

The ISF/DLR scenario was developed to limit anthropologic climate change to a maximum of 1.5 C degrees above the pre-industrial levels, in line with the aims of the Paris Climate Agreement.[84] This scenario is more ambitious than other published scenarios; for example the IEA scenario projects the global development of renewable power and electric mobility under the assumption that current policies will not change.

Renewable power generation – in particular solar PV and wind – are the most cost competitive electricity generation technologies compared to all other power generation technologies for installations and are projected to increase their market share (see Figure 4 and data in appendix). In this scenario solar PV generates 30% of electricity and wind power 33% of electricity by 2050. Lithium-ion batteries account for approximately 6% of stationary energy storage (which is dominated by pumped hydro and hydrogen).

Figure 4: Projection of 100% renewable electricity by 2050

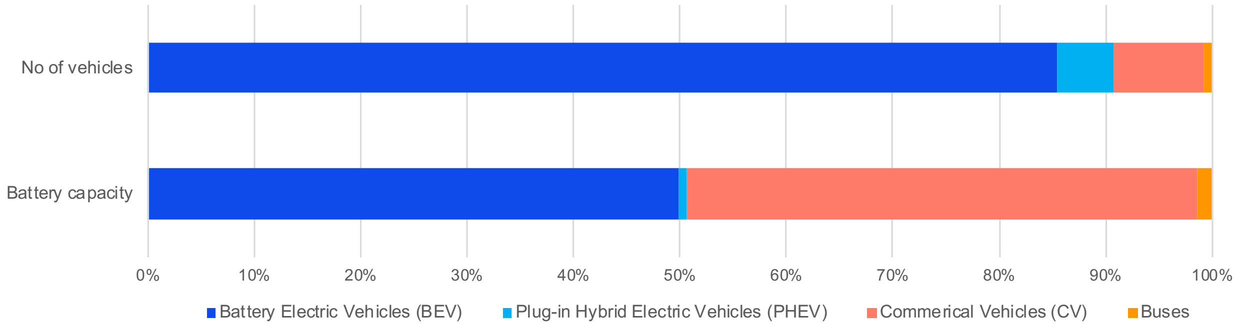


[83] See: https://oneearth.uts.edu.au/

[84] See: https://unfccc.int/resource/bigpicture/#content-the-paris-agreemen

The scenario assumes a high electrification level of the transport sector in order to replace oil as the main fuel. In the transport system we focus on the material requirements for batteries used in road transport, as other types of transport do not require batteries or are assumed to rely on other forms of energy (e.g. biofuels for aviation). In 2050 most of the energy for road transport comes from electricity (55%) and hydrogen (22%) and the remainder is from biofuels and synfuels. In the 1.5°C scenario the required batteries for electrifying road transport are given for electric buses and passenger cars, including battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), and commercial vehicles.

Figure 5: Share of vehicles and total battery capacity between vehicle types in 2050



Passenger cars (BEV and PHEV) account for 90% of vehicles and 51% of total battery capacity, whereas commercial vehicles are projected to account for 48% of battery capacity, although they make up only 9% of the total fleet of vehicles (as shown in Figure 5). This is because battery sizes for commercial vehicles (assumed to be 250 kWh in 2015 and rising to 600 kWh in 2050) are larger than those for passenger vehicles (5–15kWh for PHEV and 38–62kWh for BEV). Buses account for a small percentage (1%) of both vehicles and batteries. Electric bikes and scooters have been excluded, as although they are currently a growing market in Asia, by 2050 their share of electricity consumption is negligible compared to the predicted uptake of electric passenger and commercial vehicles.

For comparison, metal demand has also been modelled against a reference scenario that continues to have a high share of fossil fuels (with 30% renewable energy by 2050), and does not meet climate change targets.

Scenarios for metal demand

Five scenarios were developed to estimate metal demand, based on the current market trends and likelihood of changes in materials efficiency or technology described in the previous chapter (shown in Table 8).

Table 8: Summary of resource scenarios

Scenario name	Market share/ materials efficiency	Recycling	Colour in figures
Total demand	Current materials intensity and current market share of sub-technologies	No recycling	Red
Current recycling	Current materials intensity and current market share of sub-technologies	Current recycling rates	Pink
Potential recycling	Current materials intensity and current market share of sub-technologies	Improved recycling rates	Orange
Future technology	Improved materials efficiency for PV and current market share of sub-technologies Technology shift for batteries	No recycling	Dark blue
Future technology & potential recycling	Improved materials efficiency for PV and current market share of sub-technologies Technology shift for batteries	Improved recycling rates	Light blue

The predicted metals demand for renewable energy in each year is estimated based on the capacity of each technology introduced in a specific year in the energy scenario (GW of solar PV or wind power, or GWh of battery capacity for EVs and storage). This introduced stock accounts for new capacity and replacement of technologies at end of life, based on a lifetime distribution curve for the average lifetime for each technology.

The metal demand each year is then estimated based on the material intensity of a specific metal for each technology (given in Table 2). The values for metal intensity are given as tonnes/GW for solar PV and wind power, tonnes/GWh for batteries and kg/ vehicle for rare earths in EVs.

The **"total demand" scenario** is the total metal demand if the current materials intensity and market share continue into the future, without recycling or efficiency improvements. For batteries, the materials intensity is based on an assumed market share of a range of LIB technologies: NMC (60%), LMO (20%), NCA (15%), and LFP (5%).[85] For solar PV we assume the current market share of 95.8% c-Si panels (containing silver), 1.9% CIGS and 2.3% CdTe[86] and for wind we assume 20% of turbines use rare earth permanent magnet generators.[87]

Table 9: Key variables for scenarios

	Batteries	EVs	Solar PV	Wind
Lifetime	10 years	15 years	30 years	25 years
Current market share of sub-technologies	100% Li-ion	100% contain PMG	c-Si 95.8% of market, CIGS 1.9% & CdTe 2.3%	20% contain PMG
Future technology	Li-S 50% by 2050, beginning from 2030		Market share as above with improved material efficiency	

To evaluate the impact of recycling, primary demand is estimated by multiplying the discarded products at end-of-life by a recycling rate. The **"current recycling" scenario** uses the current recycling rates at end-of-life, summarised in Table 3. The **"potential recycling" scenario** uses an improved recycling which is considered to be technologically possible, but does not currently happen as it is not economic. Note for some metals there is no "current recycling" data displayed on the graph, this is because there is no recycling currently happening (e.g. silver, manganese, neodymium, dysprosium), so the result is the same as "total demand".

For metals used in batteries and solar PV we have two further scenarios, to understand the potential to offset primary demand through future improvements in technology. For batteries it is likely that the technologies used in the future will not be the same as those commercialised today (unlike solar PV and wind that are unlikely to change dramatically). Therefore, for the **"improved technology" scenario**, we assume that Lithium-sulfur batteries are the most likely technology to replace LIB for electric vehicles[88] and have a modelled a scenario of a future market where Li-S achieves a 50% market share for EVs by 2050, beginning in 2030. We assume the technology does not change for storage batteries. For solar PV, as the industry is focused more on efficiency rather than changes in technology, in the "improved technology" scenario we assume improved material efficiency using the lower values given in Table 2. The **"improved technology and potential recycling" scenario** then applies the potential recycling rate to the improved technology scenario.

Key indicators of demand

For all metals, two key indicators are analysed:

- Cumulative demand by 2050 compared to current reserves and resources, to highlight the scale of demand relative to physical availability of stocks
- Annual primary demand compared to current production across the period, to determine the amount of production in a given year and to highlight if there may be bottlenecks in supply or short term restrictions.

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[85] Based on Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, *3*, p.18013
[86] Fraunhofer Institute for Solar Energy Systems, 2018. Photovoltaics report. Available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf
[87] Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: https://www.nrel.gov/docs/fy17osti/65619.pdf
[88] Based on Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. *Nature Energy*, 3(4), p.279.

The current annual production rates, reserves and resources and shown in Table 10, based on data from the US Geological Survey and other sources.[89]

Table 10: Production rates, reserves and resources for key metals

	Annual production (tonnes)	Reserve (tonnes)	Resources (tonnes)
Aluminium	60,000,000	30,000,000,000	55 –75,000,000,000
Cadmium	23,000	500,000	6,000,000
Cobalt	110,000	7,100,000	25,000,000
Copper	19,700,000	790,000,000	3,500,000,000
Dysprosium	1,800	1,100,000	1,980,000
Gallium	315	110,000	1,000,000
Indium	720	15,000	47,000
Lithium	46,500	16,000,000	53,000,000
Manganese	16,000,000	680,000,000	unknown
Neodymium	16,000	12,800,000	23,040,000
Nickel	2,100,000	74,000,000	130,000,000
Selenium	3,300	100,000	171,000
Silver	25,000	530,000	1,308,000
Tellurium	420	31,000	48,000

Reserve and resource definitions

Reserves are the estimated amount of a mineral that can be economically mined under current conditions.[91] Reserves are a subset of resources, which are the total known amount of a mineral for which extraction may be potentially be feasible. Reserves and resources can both change over time depending on changing economic conditions, discovery of new deposits and technological developments.

Over time, resources may be reclassified as reserves, for example if higher prices and strong demand justify the mining of lower grade or more challenging ore deposits or if new technological advancements makes extraction viable. On the other hand, reserve estimates can also be downgraded over time, but are more likely to increase. Data on reserves is available for many metals, however data on resources is less certain, so reserves are more commonly used in comparing future demand to availability.[92]

This study focuses only on the metal demand for renewable energy technologies, and does not take into account other demands for these metals, which may also increase or decline over time. It is expected that renewable energy technologies will consume a greater share of these metals and in many cases may be the major driver of demand for the metal. For our projections, the potential to offset demand through recycled content comes only from metals from the same technologies at end-of-life, however demand could potentially be offset from other secondary sources of the metal. This scenario is a very ambitious renewable energy scenario based on current technologies, and over time new technologies may become more efficient or new technologies may emerge.

[89] Values for cadmium, gallium and indium reserves and resources; selenium, silver and tellurium resources and all rare earth values are from Watari, T., B. McLellan, S. Ogata and T. Tezuka, 2018. Analysis of Potential for Critical Metal Resource Constraints in the International Energy Agency's Long-Term Low-Carbon Energy Scenarios. *Minerals* 8(4): 156. All other values are from U.S. Geological Survey (USGS), 2018, Mineral commodity summaries 2018: U.S. Geological Survey. Available at: https://minerals.usgs.gov/minerals/pubs/mcs/

[91] U.S. Geological Survey (USGS), 2018, Mineral commodity summaries 2018: U.S. Geological Survey. Available at: https://minerals.usgs.gov/minerals/pubs/mcs/

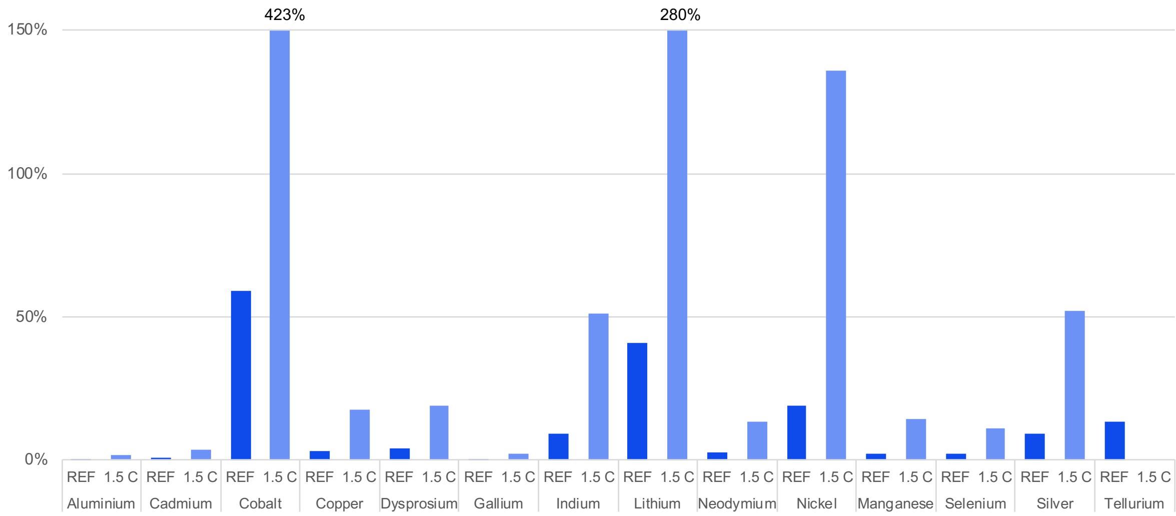
[92] Speirs, J., Gross, R., Contestabile, M., Candelise, C., Houari, Y. and Gross, B., 2014. Materials availability for low-carbon technologies: An assessment of the evidence. *UK Energy Research Centre, London.* Available at: http://www.ukerc.ac.uk/asset/34D2BFC5-9C0D-4C07-BA6CD6D15BDE549A/

3.2 Key results

Metals with high cumulative demand in 2050 compared to reserves and resources

The cumulative demand from renewable energy and storage technologies could exceed current reserves for cobalt, lithium and nickel in the 1.5 degree scenario, and demand could reach over 50% of reserves for indium, silver and tellurium. In the reference scenario, cumulative demand for cobalt is 60% of reserves and lithium is 40% of reserves, as shown in Figure 6.

Figure 6: Cumulative total demand from renewable energy and storage by 2050 compared to reserves in the 1.5 degree and Reference scenarios



Cumulative demand from the total demand scenario and the scenario with the lowest demand is shown in Table 11 and compared to reserves and resources (for the 1.5 degree scenario). Aluminium has the highest cumulative demand by 2050, followed by copper, nickel and manganese.

Table 11: Cumulative demand from renewable energy and storage by 2050 in the 1.5 degree scenario

	tonnes		**% of reserves**		**% of resources**	
	Total demand	Lowest scenario	Total demand	Lowest scenario	Total demand	Lowest scenario
Aluminium	513,866,476	443,140,185	2%	1%	1%	1%
Cadmium	18,105	11,317	4%	2%	0%	0%
Cobalt	30,067,291	9,585,532	423%	135%	120%	38%
Copper	139,539,959	101,093,179	18%	13%	4%	3%
Dysprosium	1,073,070	210,142	19%	12%	11%	7%
Gallium	2,462	1,332	2%	1%	0%	0%
Indium	7,660	4,243	51%	28%	16%	9%
Lithium	44,861,515	13,811,115	280%	86%	85%	26%
Manganese	98,446,129	31,384,886	14%	5%	0%	0%
Neodymium	92,338	1,704,713	13%	8%	7%	5%
Nickel	100,628,432	32,080,611	136%	43%	77%	25%
Selenium	11,216	7,081	11%	7%	7%	4%
Silver	276,917	152,974	52%	29%	21%	12%
Tellurium	23,181	13,074	75%	42%	48%	27%

Metals with large projected increases in demand compared to current production

Annual demand from renewable energy and storage technologies exceeds current production levels for nearly half of the metals: cobalt, dysprosium, lithium, neodymium, nickel and tellurium (as shown in Table 12). Metals that have a high projected annual demand compared to current production levels will need to rapidly increase supply. Note that these results compare peak demand to current production (2017 data) and do not account for likely increases in production that may already be planned. Lithium has the highest peak annual demand compared to current production levels, followed by cobalt.

Demand for lithium, cobalt and rare earths from renewable energy exceeds current production rates by 2022. The rapid increase for these metals is owing to the predicted rapid electrification of the transport system, which has only begun to accelerate in the last few years. This is in comparison to the more established technologies of solar PV and wind, which have already been rolling out at rapid rates.

Table 12: Peak annual demand from renewable energy and storage compared to current production (2017 data) in the 1.5 degree scenario

	tonnes		% of annual production		Year of peak demand	
	Total demand	Lowest scenario	Total demand	Lowest scenario	Total demand	Lowest scenario
Aluminium	18,852,177	17,822,832	3%	3%	2036	2033
Cadmium	700	479	3%	2%	2035	2028
Cobalt	1,966,469	747,427	1788%	679%	2050	2031
Copper	5,626,579	4,493,216	29%	23%	2050	2033
Dysprosium	11,524	7,299	640%	406%	2050	2031
Gallium	89	57	28%	18%	2035	2028
Indium	276	181	38%	25%	2035	2028
Lithium	4,112,867	727,682	8845%	1565%	2050	2033
Manganese	6,438,599	2,447,220	40%	15%	2050	2031
Neodymium	94,687	59,118	592%	369%	2050	2031
Nickel	6,581,326	2,501,469	313%	119%	2050	2031
Selenium	404	289	12%	9%	2035	2028
Silver	9,926	6,646	40%	27%	2035	2027
Tellurium	834	555	199%	132%	2035	2028

The year at which demand for each metal peaks is shown in Table 12. For metals for which solar is the main source of demand, peak demand is around 2035/36, whereas for all other metals peak annual demand occurs in 2050. In the lowest demand scenario for each metal, peak annual demand occurs earlier (between 2027-2033), as the effects of recycling or shifting technology take effect.

Potential to offset demand

The potential to offset primary demand for each metal depends on the technology which is the dominant driver of demand.

For metals in batteries, the scenarios show that recycling has the biggest impact on reducing primary demand. This is shown in Figure 7, where the cumulative demand in the "potential recycling" scenario is significantly lower than the total demand scenario. Shifting away from Lithium-ion batteries which use cobalt and nickel also has a large impact on reducing demand for these metals, which is even greater when combined with recycling (as shown in the "new technology & potential recycling scenario"). However, this increases the demand for lithium which is used in greater amounts in Li-S batteries under the scenario. These results are based on recycling at end-of-life of the technologies in this study, and using recycled metals from other sources could further reduce primary demand.

Figure 7: Cumulative demand from EVs and battery storage by 2050 relative to reserves in three scenarios

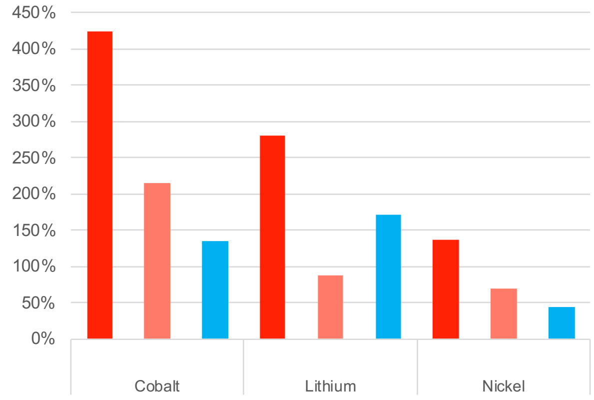
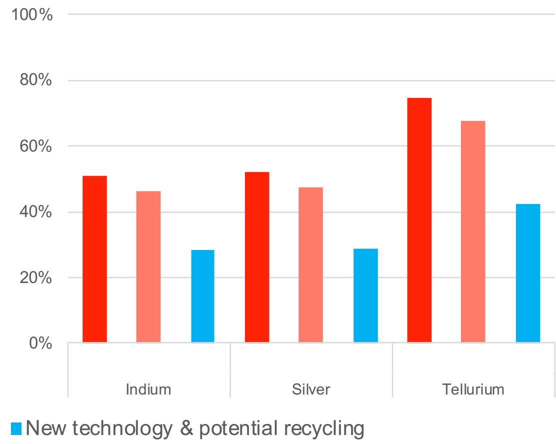


Figure 8: Cumulative demand from solar PV relative to reserves in three scenarios



Material efficiency has the most potential to offset primary demand for solar PV metals, rather than recycling. This is because the long lifetime of PV panels creates a lag for when the materials in PV panels become available for recycling. This is represented in Figure 8, where the “new technology & potential recycling” scenario has a much larger impact on cumulative demand compared to the “potential recycling” scenario.

Share of demand between technologies

Solar PV is the main driver of demand for aluminium across the entire period (Figure 9). Solar PV is also the main consumer of copper until 2035, and after this batteries dominate the consumption (Figure 10). In considering battery demand, EVs are the main source of demand for lithium, cobalt and other battery metals, rather than stationary storage. EVs, rather than wind power, are projected to drive demand for rare earths neodymium and dysprosium (Figure 11). The share of demand in the total demand (red) and potential recycling (orange) scenarios is shown below.

Figure 9: Share of primary demand for aluminium from wind, solar PV and batteries

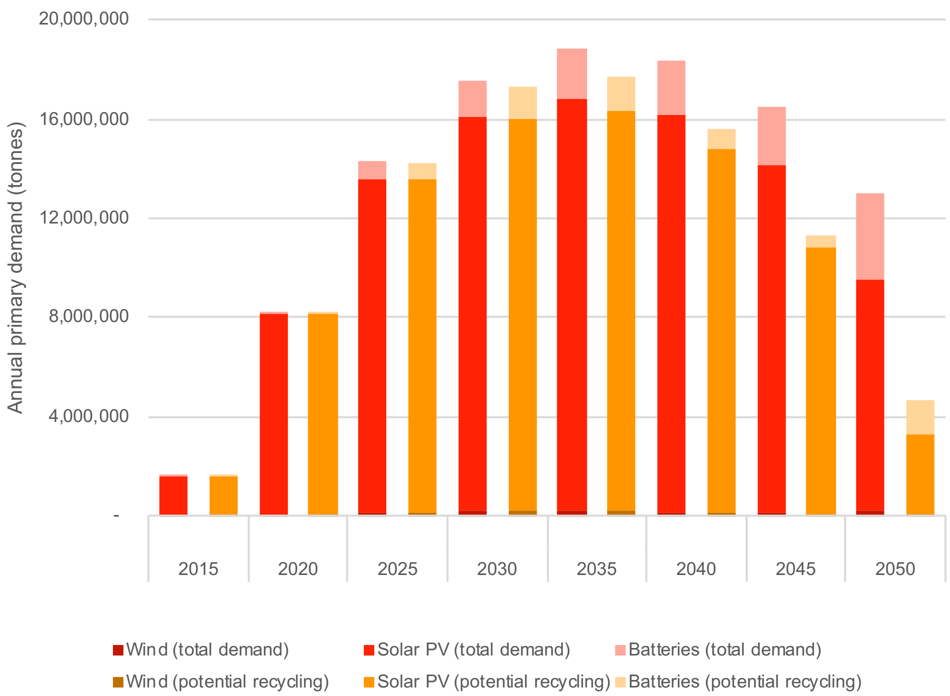


Figure 10: Share of primary demand for copper from wind, solar PV and batteries

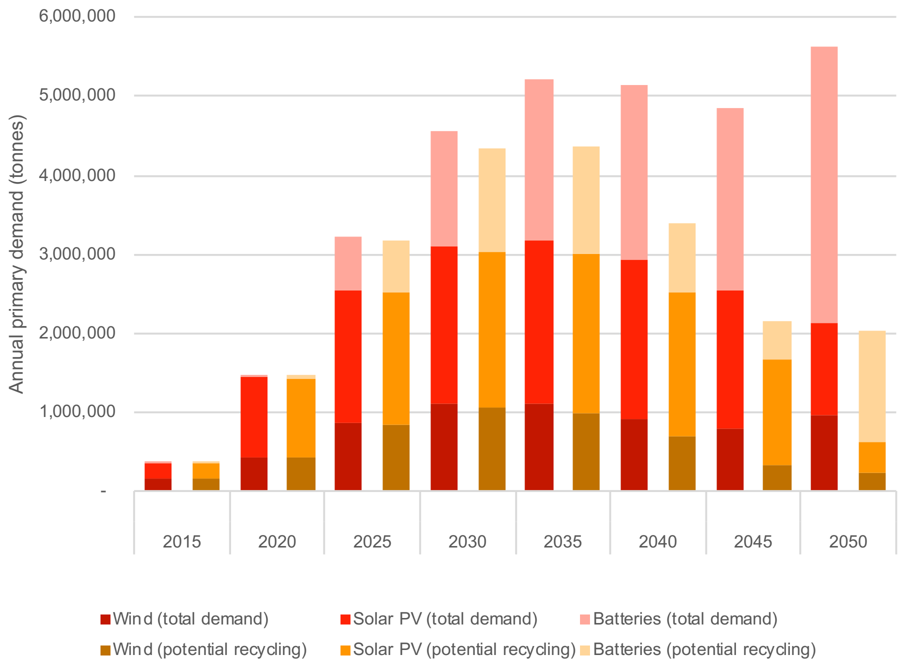
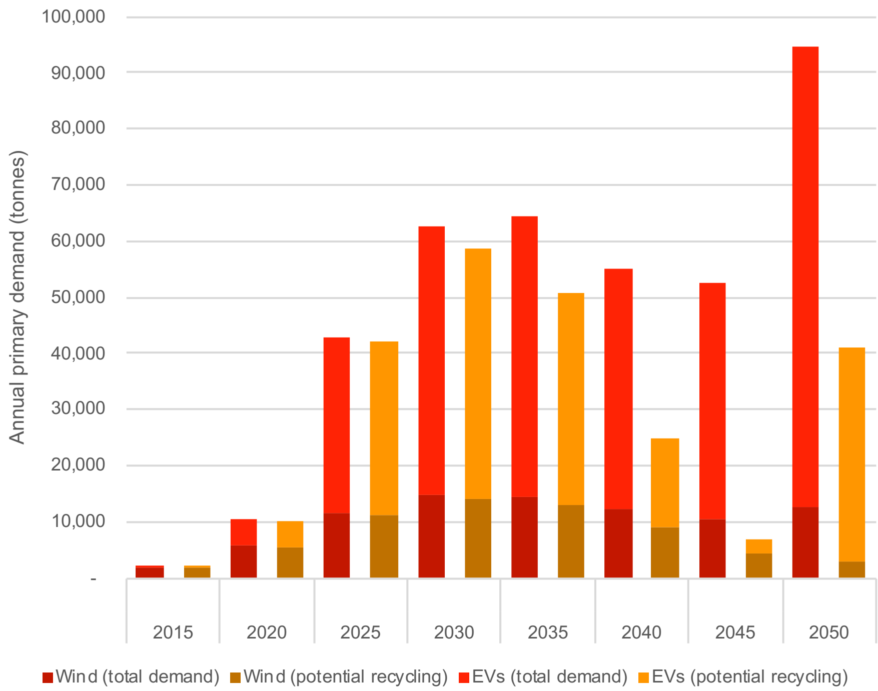


Figure 11: Share of primary demand for neodymium from wind and EVs[93]



Demand from solar PV for aluminium and copper peaks in 2035, as this period is assumed to have the largest increase in installations, as shown in Figure 10 and 11. Similarly, demand from wind for aluminium, copper and neodymium peaks in 2030, but then begins to increase again to replace end-of-life turbines. The deployment of batteries (mainly in EVs) increases over the period, but the annual demand varies with the replacement of end-of-life batteries. The effect of recycling EVs and batteries in the "potential recycling" scenario results in an earlier peak demand for copper and neodymium than in the "total demand" scenario. Overall batteries and solar PV have the greatest impact on demand, and detailed results for key metals for these technologies are shown in the following sections.

[93] The share of demand for dysprosium is similar to neodymium, as they are found in similar proportions in the two technologies

3.3 Batteries for EVs and stationary storage

Cobalt and lithium have an annual demand from batteries for EVs and storage that far exceeds current rates of production. Annual demand for cobalt and lithium could exceed current production rates by around 2023, in all scenarios.

Shifting to Li-S instead of LIB decreases demand for cobalt (shown in the “future technology” scenario). However, unless this shift happens alongside high recycling rates this has less impact on reducing primary demand than continuing with the current technology and recycling rates (the “current recycling” scenario). In the scenario of “future technology & potential recycling” the demand for cobalt could actually drop below current annual production by 2042 (Figure 12).

The shift to Li-S batteries increases demand for lithium, as these batteries have around three times the amount of lithium compared to LIB. Increasing recycling from current minimal levels (assumed 10%) has the most potential to offset primary demand for lithium (Figure 13).

Figure 12: Annual primary demand from EVs and battery storage for cobalt

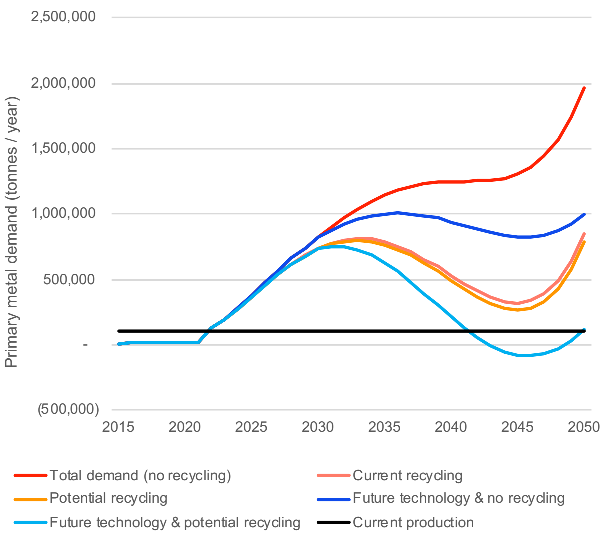
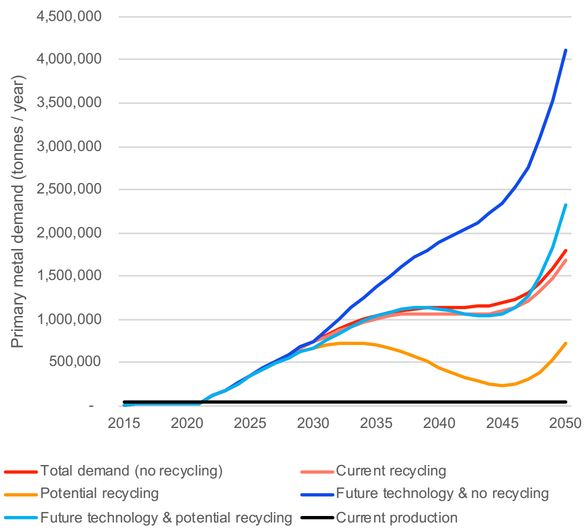


Figure 13: Annual primary demand from EVs and battery storage for lithium



Cumulative demand for cobalt from batteries for EVs and storage exceeds current reserves in all scenarios (Figure 14), and for lithium it is exceeded in all scenarios except for the “potential recycling scenario” (Figure 15).

Figure 14: Cumulative primary demand by 2050 from EVs and battery storage for cobalt

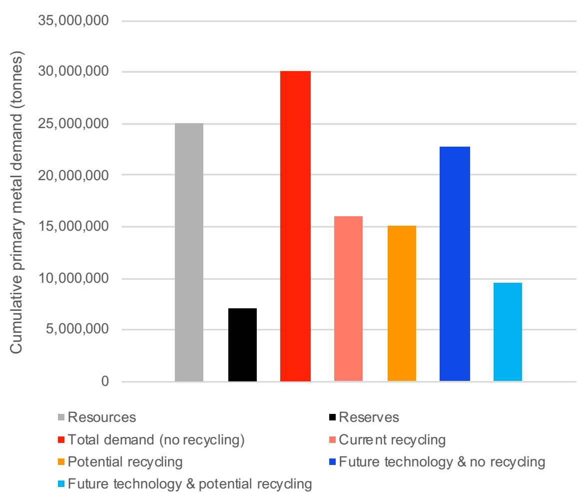
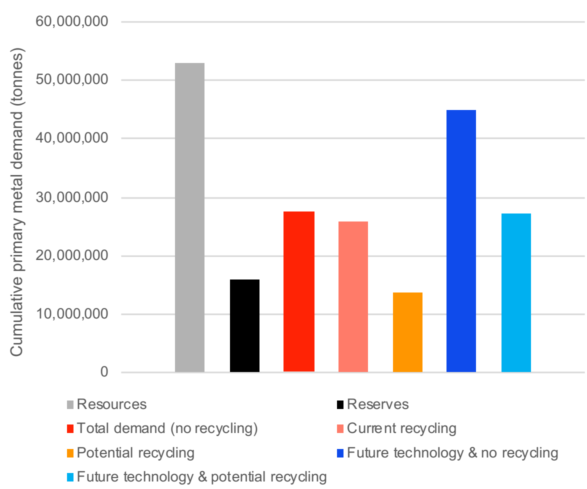


Figure 15: Cumulative primary demand by 2050 from EVs and battery storage for lithium



3.4 Solar PV

The annual demand from solar PV for silver could reach more than 40% of current production rates by 2050 in the "total demand" scenario (assuming no recycling and materials efficiency does not change) (Figure 16). Annual demand for tellurium could exceed current production rates by 2020, and demand could peak at 200% of current production in around 2035 (Figure 17). The point at which demand exceeds current production happens a few years later in the future technology scenario because of improved materials efficiency.

Figure 16: Annual primary demand from solar PV for silver

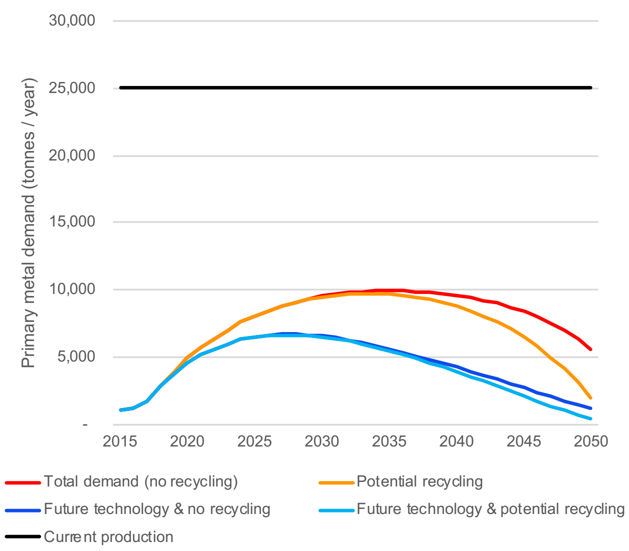
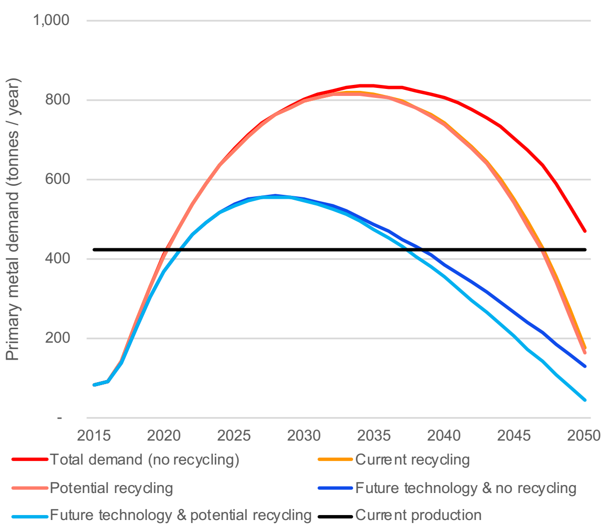


Figure 17: Annual primary demand from solar PV for tellurium



Cumulative demand for silver by 2050 could reach around half of current reserves in the "total demand" scenario, and around one-quarter if there is improved technology (Figure 18). For tellurium, cumulative demand by 2050 could reach two-thirds of current reserves with current technology, and around one-third if there is improved technology (Figure 19).

Figure 18: Cumulative primary demand by 2050 from solar PV for silver

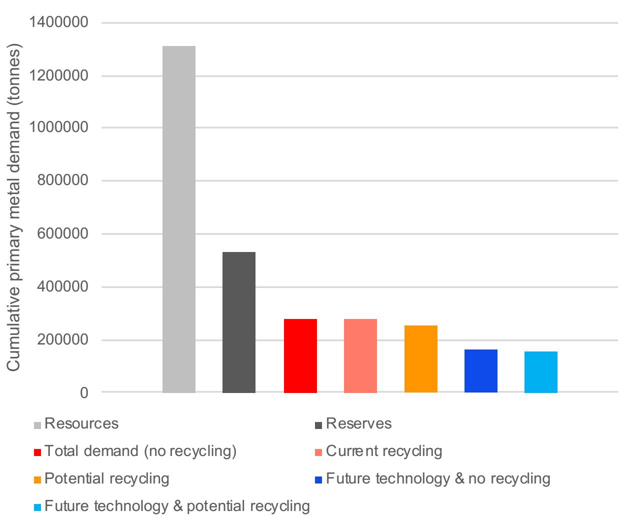
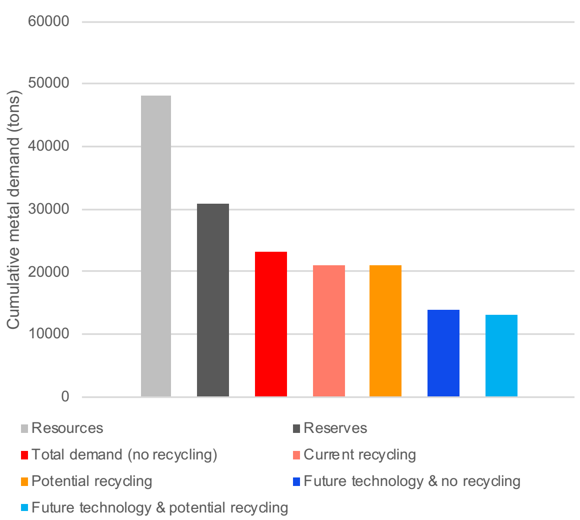


Figure 19: Cumulative primary demand by 2050 from solar PV for tellurium



For both metals, the reduction of material intensity in the "future technology" scenario has the greatest potential to reduce demand compared to the "total demand" scenario, and this is reduced further if recycling is included.

3.5 Summary of projected metal demand

Cobalt and lithium are the metals of highest concern for future demand, as they have a high cumulative demand compared to reserves and resources, as well as high annual demand compared to current production.

For all metals the cumulative demand was compared against reserves and resources to determine if there could be long-term issues with the availability of supply. Cobalt, lithium and nickel all exceed reserves; demand for indium, silver and tellurium could reach over 50% of reserves. For other metals, including rare earths, neodymium and dysprosium, there will be projected large increases in demand compared to current annual production, but no issues with long-term supply. The summary of risks from the demand projections is shown in Table 13.[94]

The metals with high cumulative demand compared to reserves are the metals where marginal or unconventional resources are likely to be accessed, as easily accessible reserves will be exhausted soonest. These are often in more remote or biodiverse places, such as conservation areas or the ocean floor.[95] These metals are most likely to face volatile prices and issues with security of supply, as has already been observed for cobalt and lithium. A rapid increase in demand compared to production indicates the likelihood of the expansion or development of new mines in the near future, which is discussed for cobalt, lithium and rare earths in the next chapter.

Table 13: Summary of risks from future demand projections

		Annual demand in 2050 compared to current production		**Cumulative demand compared to reserves & resources**
Aluminium		< 5% of production in all scenarios		< 5% of reserves in all scenarios
Cadmium		< 5% of production in all scenarios		< 5% of reserves in all scenarios
Cobalt		> 500% of production in all scenarios		> 100% of reserves in all scenarios and resources in total demand scenario
Copper		< 50% of production in all scenarios		< 20% of reserves in all scenarios
Dysprosium		> 500% of production in all scenarios		< 20% of reserves in all scenarios
Gallium		< 50% of production in all scenarios		< 5% of reserves in all scenarios
Indium		< 50% of production in all scenarios		> 50% of reserves in highest scenario
Lithium		> 100% of production in all scenarios		> 100% of reserves in most scenarios
Manganese		< 50% of production in all scenarios		< 20% of reserves in all scenarios
Neodymium		> 500% of production in all scenarios		< 20% of reserves in all scenarios
Nickel		> 100% of production in all scenarios		> 100% of reserves in highest scenarios
Silver		< 50% of production in all scenarios		> 50% of reserves in highest scenario
Selenium		< 20% of production in all scenarios		< 20% of reserves in all scenarios
Tellurium		> 100% of production in all scenarios		> 50% of reserves in highest scenario

[94] For ranking the risk from annual demand in 2050 compared to production, red represents metals have demand more than 500% of current production in all scenarios, orange represents metals where demand is greater than 100% and yellow for metals that are less than 50% in all scenarios. For ranking cumulative demand, red represents metals that exceed reserves in any scenario, orange represents metals where demand is greater than 50% of reserves in any scenario and yellow for metals that are less than 50% of reserves in all scenarios.
[95] WWF, n.d. Responsible oil, gas and mining. Available at: https://www.wwf.org.uk/what-we-do/area-of-work/responsible-oil-gas-and-mining

4 Supply risks

4.1 Concentration of production and reserves

Mining to supply renewable energy technologies occurs in a large number of countries, but a smaller number of countries dominate production. China is the largest producer of metals used in solar PV and wind technologies, with the largest share of production for aluminium, cadmium, gallium, indium, rare earths, selenium and tellurium. In addition, China also has a large influence over the market for cobalt and lithium for batteries. While Australia is the largest producer of lithium, the majority of this is shipped to China for processing. The largest lithium mine, Greenbushes in Western Australia, is majority owned by a Chinese company. Similarly, while DR Congo mines more than half of the world's cobalt, China is the leading producer of refined cobalt, 90% of which is sourced from DR Congo through the many Chinese mining companies and trading houses in the region.[96] With a large share of the manufacturing of solar PV and lithium-ion batteries, China is also a large end-market for many of the metals, as well as the largest market for the technologies.

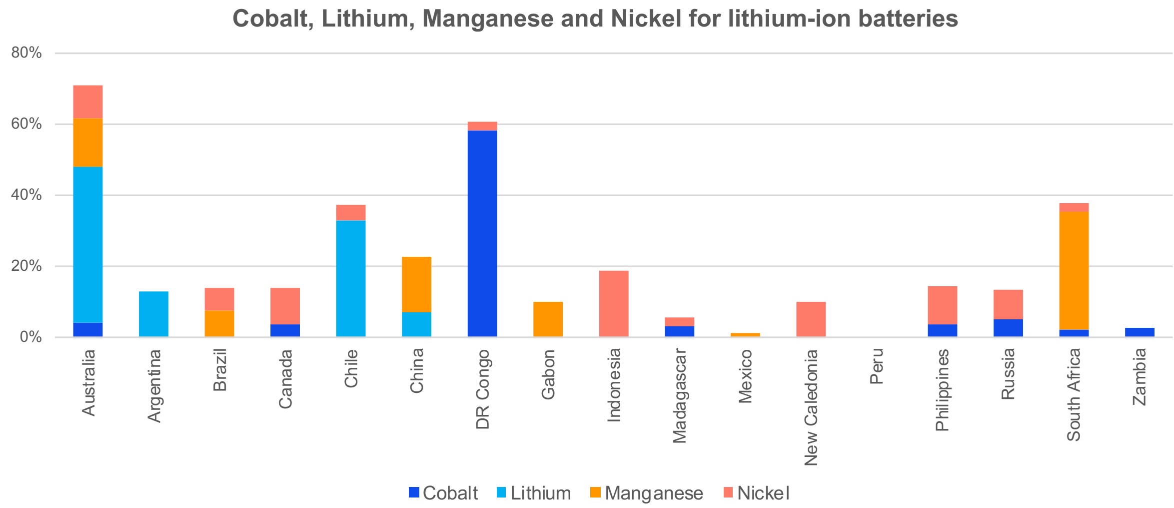
Australia, Chile, DR Congo and South Africa have large shares of the production of metals for lithium-ion batteries. Japan, Korea, Canada and Russia have significant production levels of metals for PV, in addition to China (shown in Figure 20). The countries with the highest share of current production and proven reserves for each of the metals are presented in Table 14.[97] The data presented below highlights reserves, which is the subset of total resources that can be economically mined, which are dependent on a multitude of factors and can change over time.

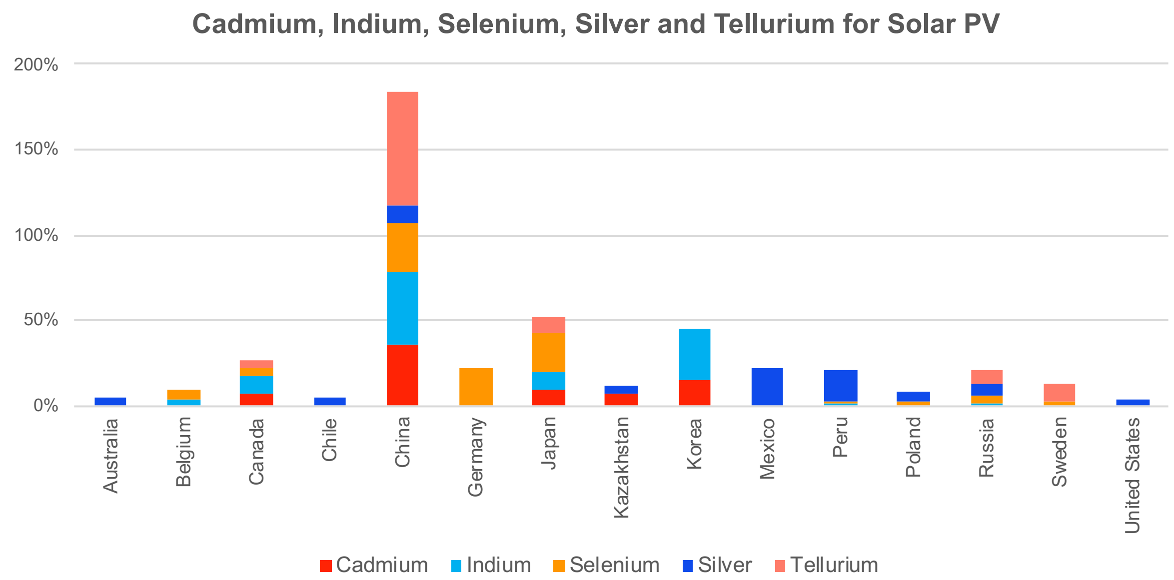
Table 14: Share of current supply and reserves (2017)[98]

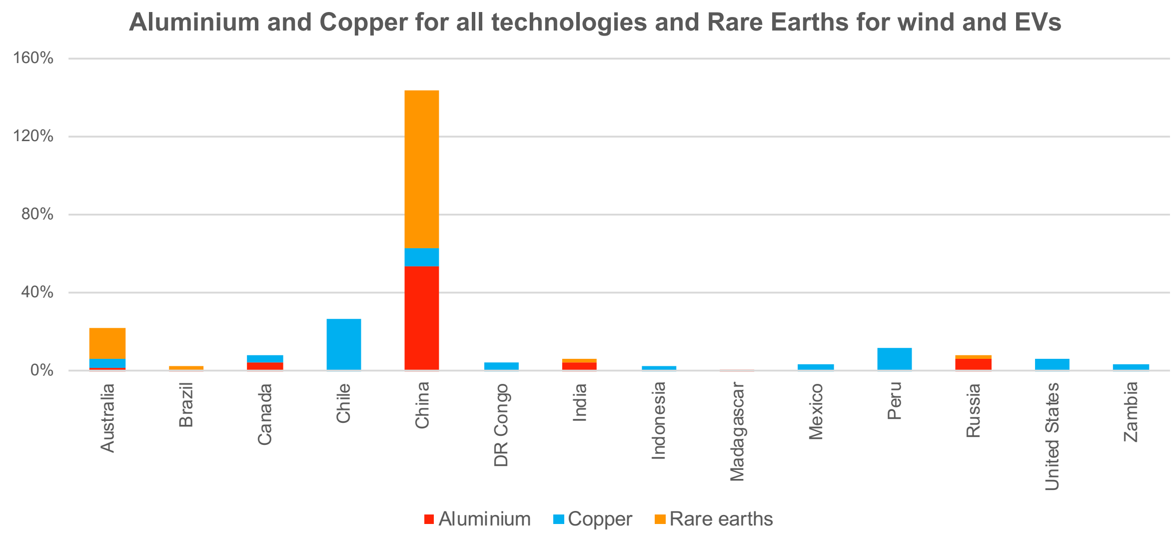
	Share of current production	Share of reserves
Aluminium	Aluminium smelter production: China 54%, Russia 6%, Canada 5%, India 5%	Bauxite and aluminia reserves: Australia 20%, Vietnam 12%, Brazil 9%, Jamaica 7%
Cadmium	China 36%, Korea 16%, Japan 10%	Share of reserves unknown
Cobalt	DR Congo 58%, Russia 5%, Australia 5%, Canada 4%, Cuba 4%	DR Congo 49%, Australia 17%, Cuba 7%, Zambia 4%, Canada 4%, Russia 4%
Copper	Chile 27%, Peru 12%, China 9%, United States 6%	Chile 22%, Peru 12%, China 9%, United States 6%, Australia 5%
Gallium	China, Japan, Slovakia, United Kingdom, United States (high grade, share unknown)	Share of reserves unknown
Indium	China 43%, Korea 30%, Japan 10%, Canada 10%	Share of reserves unknown
Lithium	Australia 40%, Chile 30%, Argentina 12%, United States 8%, China 7%	Reserves: Chile 47%, Australia 17% Resources: Argentina 18%, Bolivia 17%, Chile 16%, United States 13%, Australia 9%, Canada 4%
Manganese	South Africa 33%, China 16%, Australia 14%, Gabon 10%	South Africa 29%, Ukraine 21%, Brazil 18%, Australia 14%
Nickel	Indonesia 19%, Philippines 11%, New Caledonia 10%, Canada 10%	Brazil 16%, Cuba 7%, Indonesia 6%, Philippines 6%
Rare Earths[99]	China 81%, Australia 15%, Russia & Brazil 2%	Brazil 18%, Vietnam 18%, Russia 15%, India 6%
Silver	Mexico 22%, Peru 18%, China 10%	Peru 18%, Poland 17%, Australia 17%, Russia 10%
Selenium	China 28%, Japan 23%, Germany 22%	China 26%, Russia 20%, Peru 15%
Tellurium	China 67%, Sweden 10%, Russia 8%	China 21%, Peru 12%, United States 11%, Canada 3%

[96] Frankel, T.C., 2016. The Cobalt pipeline. *Washington Post*. Available at: https://www.washingtonpost.com/graphics/business/batteries/congo-cobalt-mining-for-lithium-ion-battery/?tid=batteriesbottom.
[97] Both Table 14 and Figure 27 present the share of total production, it is not known which countries are producing for use in clean technologies compared to other uses, particularly for metals which clean energy technologies are not a major consumer.
[98] Data for 2017 from U.S. Geological Survey (USGS), 2018, Mineral commodity summaries 2018: U.S. Geological Survey. Available at: https://minerals.usgs.gov/minerals/pubs/mcs/
[99] Includes Dysprosium and Neodymium

Figure 20: Share of production for renewable energy technologies by country (2017)

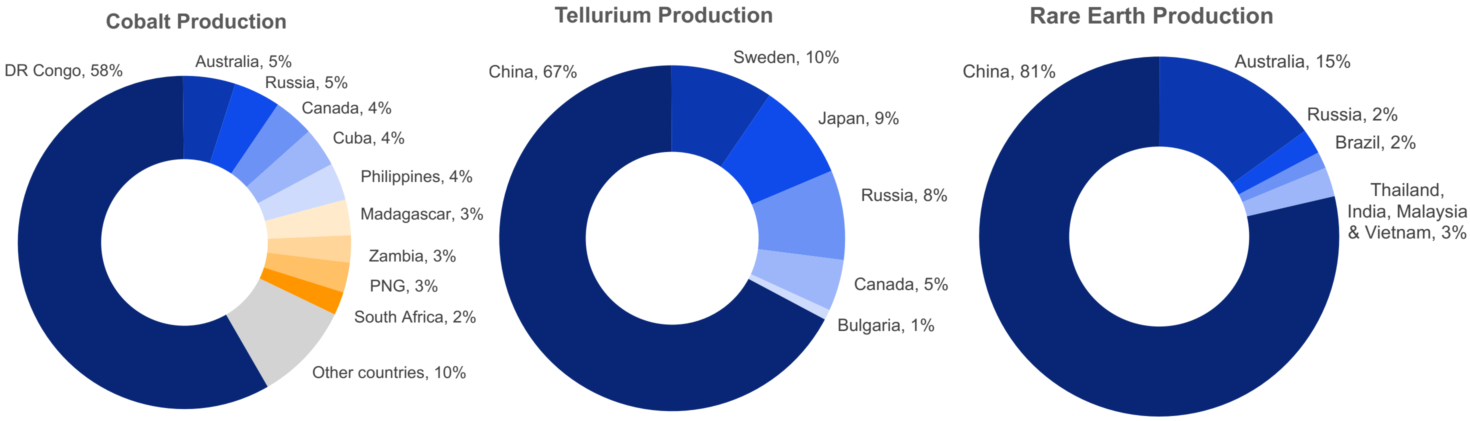






The metals where production is most dominated by a single country are Rare Earths and Tellurium (China) and Cobalt (DR Congo). These are shown in Figure 21. In addition, DR Congo also has around half of current reserves of cobalt, but there are large global resources. The metals with the most concentrated production and reserves are also highlighted in Table 16 at the end of this section.

Figure 21: Production by country for cobalt, rare earths and tellurium (2017)

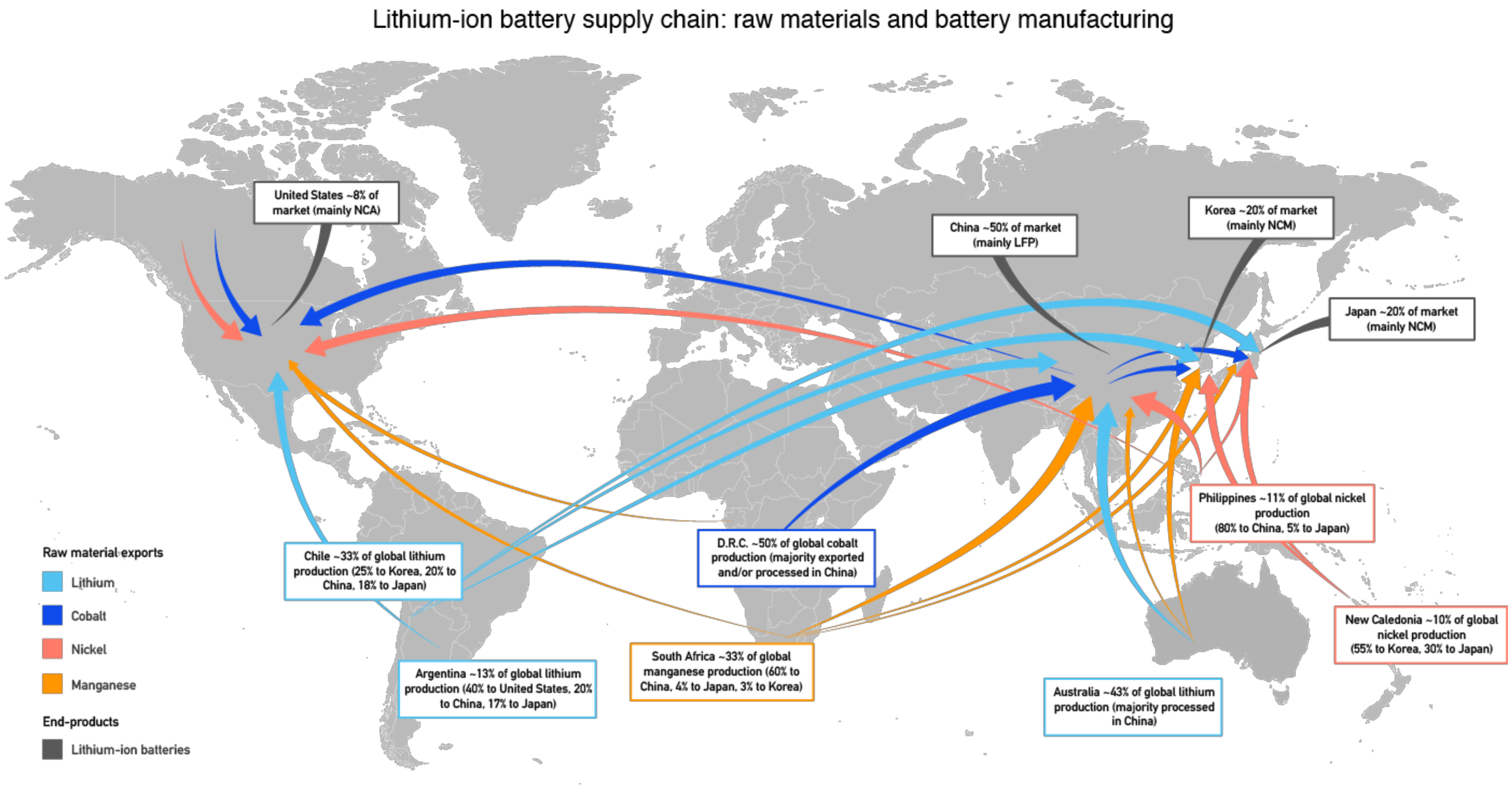


Generally, countries that have a large share of current production have the most potential to be able to increase supply in the short term, as they have existing resources in place required to bring a new mine in to operation. In addition, countries with existing mining are more likely to have the technological knowledge, infrastructure in place and social licence to operate. However, this does not always mean that they have the largest reserves or resources available.

Considering long term supply, for many metals there are countries that have a large share of global reserves or resources, but do not currently mine or have only a small amount of production (as shown in Table 14). Looking again at Rare Earths, Brazil (18%), Vietnam (18%) and Russia (15%) have a significant share of global reserves, but currently only have a very small share of production (less than 2% each). Other examples include Ukraine and Brazil, each with around 20% of manganese reserves, but currently only contribute 1% of world production each. Similarly, Brazil and Cuba may be long term sources for nickel, alongside existing producers.

Countries that have large reserves of several metals for which they only mine a small share of global production include Australia (cobalt and silver), Brazil (manganese, nickel and rare earths), Peru (selenium, tellurium and copper). Bolivia has the second largest share of the worlds' lithium resources but does not currently mine lithium. These countries have potential to be long term sources for these metals, alongside existing producers. However, there are many other considerations that will affect where mining expands or new mining takes place, including social, economic, technological and environmental factors.

Figure 22: Overview of lithium-ion battery supply chain[71]



100 Based on Comtrade data available at: https://comtrade.un.org/data/

4.2 Where mining is likely to expand

Under a 100% renewable energy scenario metal requirements are projected to rise dramatically. Although secondary can sources significantly reduce primary demand, especially for batteries, there is a time delay for when recycling can reduce demand the metals. New mining is likely to take place to meet demand, and new mines are already under development.

The uptake of electric vehicles has already increased the demand of cobalt and lithium for lithium-ion batteries, and is the main driver of new demand for these metals. There is also increased demand for rare earths, including neodymium and dysprosium used for electric motors (as well as other rare earths used in a range of technologies). A large number of mines to create new supply for these metals are in development or exploration stages. In this section we review the expansion of mining for the key metals for electric vehicles, as this is the market that is expected to rapidly increase in the next decade, whereas PV and wind turbines are more mature technologies so the increase in demand will likely be steadier. The existing main sources for battery materials are shown in Figure 22.

Cobalt

Cobalt is often produced as a by-product alongside nickel, copper or gold, however several new projects are solely targeting cobalt rather than as a by-product, reflecting the predicted high future demand. Notable new cobalt developments are underway in Australia, Canada and the United States, and further mines are proposed in the DR Congo. There are plans for the expansion and development of nickel mines in Indonesia and Vietnam, and a copper project in Panama, which plan to produce cobalt as a by-product, although the development of these mines is less certain.

Lithium

Lithium can be sourced from hard-rock ore (spodumene), from the evaporation of salt brines and from seawater. Lithium sourced from salt brines dominated the market in the 1990s due to lower production costs, however the current market share for brine and spodumene is roughly equal.[101]

Chile is the major producer of lithium from salt brines, in the form of lithium carbonate (Li_2CO_3), alongside Argentina who began commercial production from a new mine in 2015. Australia is the leading producer of lithium from spodumene and produces a concentrate containing lithium oxide (Li_2O).[102] Historically, lithium carbonate from South America has been the main material for battery manufacture, whereas lithium oxide from hard rock was mainly used in the glass and ceramics industries.[103] However, the global supply chain is interlinked, and China processes lithium carbonate for use in battery manufacture from spodumene from Australia, as well as domestic mining of both spodumene and brines.[104]

Expansion and development of new brine operations is underway in Argentina, Chile and the United States, as well as hard rock operations in Australia, Canada, China and Finland. While Bolivia has the largest resources of lithium, estimated at 9 million tonnes, there has been slow development of mining due to mining policies that restrict foreign investment and resistance from indigenous groups.[105] The country is currently looking to ramp up production from the Uyuni mine site, which is producing only 10 tonnes per month, but foreign companies are hesitant to invest.[106] Bolivia also faces economic challenges compared to neighbouring Argentina and Chile, including higher levels of

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101 Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., 2017, Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, 797 Available at: http://doi.org/10.3133/pp1802

102 Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., 2017, Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, 797 Available at: http://doi.org/10.3133/pp1802

103 Dunn, J.B. et al., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy Environ. Sci.*, 8(1), pp.158–168. Available at: http://dx.doi.org/10.1039/C4EE03029J%5Cnhttp://xlink.rsc.org/?DOI=C4EE03029J.

104 Prior, T. et al., 2013. Sustainable governance of scarce metals: The case of lithium. *Science of the Total Environment*, 461–462, pp.785–791. Available at: http://dx.doi.org/10.1016/j.scitotenv.2013.05.042.

105 Romero, S., 2009. In Bolivia, untapped bounty meets nationalism. *New York Times*. Available at: http://www.nytimes.com/2009/02/03/world/americas/03lithium.html.

106 Alper, A. 2017., Bolivia seeks investors to power up lagging lithium output. *Reuters* https://www.reuters.com/article/us-bolivia-lithium-analysis/bolivia-seeks-investors-to-power-up-lagging-lithium-output-idUSKBN1EL1JB

magnesium in the brine which makes it more difficult to refine, poor infrastructure, and relatively high transport costs to get to markets in Asia and North America as it is a landlocked country.[107]

Rare Earths

Rare earths are found in many regions of the globe, however they are often not found in economically viable concentrations and are difficult to extract.[108]

The United States was the main producer of rare earths until the 1990s until the closure of the major US mine, which was unable to compete with Chinese production and faced environmental issues. China was able to gain an economic advantage in rare earth production, particularly as the biggest rare earth mine also produces iron ore which makes the mine more profitable. Chinese production soared following the closure of the US mine, and in 2002 China was producing 97% of the worlds' rare earths. A major mine at Mt Weld in Western Australia and associated processing facility in Malaysia and new investments in the United States in 2013 have somewhat reduced China's domination of the market.[109]

There are major new mines under development in Australia, Canada, Greenland and South Africa, as well as interests in Malawi and Uganda.[110]

A list of the mines set to come into production in the next two years is shown in Table 15, with those likely to create significant supply in the short term in bold. This table also includes several existing mines that have started to expand their operations.

Table 15: New supply for key metals (at development stage or set to come online in next two years)[111]

Cobalt

Australia	• **Clean TeQ Sunrise** in New South Wales owned by Clean TeQ Holdings (China's Pengxin International Mining holds 16.5% stake) • Niwest owned by GME Resources • Kalgoorlie Nickel owned by Ardea Resources
Canada	• **NICO** in Northwest territories owned by Forture Minerals corp
DR Congo	• **KCC material assets** owned by Katanga Mining Ltd (KML) (75%) and Kamoto Copper Company (KCC) (25%) • Kipoi Central 60% owned by Tiger Resources
Indonesia	• Weda Bay jointly owned by Eramet and Tsingshan group
United States	• **Idaho Cobalt** owned by eCobalt • **Northmet** in Minnesota owned by Polymet Mining Corp.
Panama	• Cobre Panama owned by First Quantum Minerals
Vietnam	• Extension of Ban Phuc owned by Asian Mineral Resources (90%)

Nickel

Zambia	• Restart of the Munali Nickel Project, owned by Consolidated Nickel Mines (CNM) (UK company). The mine ceased operations in 2011 due to low nickel prices and operational problems by previous owners.

[107] Mazumdaru, S. 2017, Bolivia's Evo Morales plans lithium mining offensive *DW* https://www.dw.com/en/bolivias-evo-morales-plans-lithium-mining-offensive/a-39727810
[108] Kuan, S.H., Saw, L.H. and Ghorbani, Y., 2016., A review of rare earths processing in Malaysia. Universiti Malaysia Terengganu International Annual Symposium on Sustainability Science and Management (UMTAS2016)
[109] Gholz, E., 2014., Rare Earth Elements and National Security. Council on Foreign Relations. Available at: https://cfrd8-files.cfr.org/sites/default/files/pdf/2014/10/Energy%20Report_Gholz.pdf
[110] Hoenderdaal, S., Espinoza, L.T., Marscheider-Weidemann, F. and Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies?. *Energy*, 49, pp.344-355.
[111] Data for cobalt, lithium and nickel compiled from Ali A., Toledano, P., Maennling, N., Hoffman, N. Aganga, L., 2018. Resourcing Green Technologies through Smart Mineral Enterprise Development: A Case Analysis of Cobalt. *Columbia Center on Sustainable Investment at Columbia University* and The Assay Group Mining Magazine, The Battery Materials Edition, February 2018. Available at: http://neometals.com.au/reports/the-assay-the-assay-battery-materials.pdf
Data for rare earths from Hoenderdaal, S., Espinoza, L.T., Marscheider-Weidemann, F. and Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies?. *Energy*, 49, pp.344-355.

Lithium

Argentina	• **Cauchari-Olaroz** jointly owned by Lithium Americas and SQM • Salar de Centenario owned by Eramet • Sal de Vida owned by Galaxy Resources Ltd (Australian company) • Sal de Los Angeles owned by Lithium X Energy Corp. • Tres Quebradas owned by Neo Lithium Corp. (Canadian company)
Australia	• **Expansion of Greenbushes** jointly owned by Tianqui Lithium (51%) and Albermarle (49%) via Talison Lithium • **Pilgangoora** by Altura Mining • **Mt Marion** owned by Mineral Resources Limited (43.1%), Jiangxi Ganfeng Lithium Co., Ltd (43.1%) and Neometals Ltd (13.8%)
Bolivia	• Salar de Uyuni owned by Comibol
Chile	• Planta Salar owned by Rockwood Lithium
Canada	• **Whabouchi** owned by Nemaska Lithium • Authier owned by Sayona Mining
Mexico	• **Sonora Lithium** owned by Bacanora Minerals (70%) and Cadence Minerals (30%)
Serbia	• Jadar owned by Rio Tinto
United States	• Expansion of Silver Peak owned by Albermarle

Rare Earths

Australia	• **Expansion of Mount Weld** in Western Australia owned by Lynas Corporation Ltd and processed at the Lynas Advanced Material Plant (LAMP) near Kuantan, Malaysia[112] • Nolans in Northern Territory, owned by Arafura Resources[113] • Dubbo Project in New South Wales, owned by Australian Strategic Materials Limited (ASM), a wholly owned subsidiary of Alkane Resources Ltd.[114] • Browns Range in Western Australia, owned by Northern Minerals[115]
Canada	• **Thor Lake** owned by Avalon Advanced Materials Inc.[116] • Hoidas Lake in Northern Saskatchewan owned by Navis Resources[117] • Alces Lake in Northern Saskatchewan owned by Appia Energy Corp.[118] • Port Hope Simpson CREE District, Henley Harbour Area and Red Wine Complex Labrador, owned by Search Minerals Inc.[119]
Greenland	• **Kvanefjeld, Sørensen, and Zone 3** owned by Greenland Minerals Ltd (Australian company)[120]
Malawi	• Songwe Hill in Southwestern Malawi, owned by Mkango (Canadian company)[121]
South Africa	• **Steenkampskraal Mine** in Western Cape owned by Steenkampskraal Holdings Ltd.[122] • Zandkopsdrift owned by Frontier Rare Earths
Uganda	• Mukuutu project owned by Rwenzori Rare Metals Limited, a private Ugandan company that is 85% owned by the private investor Rare Earth Elements Africa (Pty) Ltd (South African company)[123]

[112] Lynas Coporation, 2018., Mt Weld, Western Australia. Available at: https://www.lynascorp.com/Pages/Mt-Weld-Concentration-Plant.aspx
[113]Arafura Resources, 2018., Nolans. Available at: https://www.arultd.com/projects/nolans.html
[114] Alkane Resources, 2018., Dubbo project. Available at: http://www.alkane.com.au/operations/dubbo-project/
[115] Northern Minerals, 2018, Browns Range. Available at: http://northernminerals.com.au/future-prospects/browns-range/
[116] Avalon Advanced Materials Inc., 2018. Available at: http://avalonadvancedmaterials.com/nechalacho/
[117] Navis Resources, 2018, Hodias Lake. Available at: http://naviscorp.com/properties/hoidas-lake
[118] Appia Energy Corp, 2018, News Release: Appia Provides Update on the Critical Rare Earth Element Exploration Program on Its Alces Lake Property. Available at: http://www.appiaenergy.ca/_resources/news/nr_20180802.pdf
[119] Search Minerals Inc., 2018, Projects. http://www.searchminerals.ca/projects
[120] Greenland Minerals Ltd, 2018, The Ilimaussaq Complex. Available at: http://www.ggg.gl/project/geology-and-resource/
[121] Mkango, 2018. Songwe Hill. Available at: http://www.mkango.ca/s/songwe.asp
[122] Steenkampskrall Holdings Ltd., 2018. Available at: http://www.steenkampskraal.com/the-mine/
[123] Rwenzori Rare Metals, 2018. Available at: https://rwenzoriraremetals.com/

4.3 Renewable energy share of consumption

The share of consumption of a metal by renewable energy technologies will affect growth in demand and supply risks. Metals for which renewable energy is a high share of total demand will have more need to increase supply. It also means that changes or potential restrictions in the supply of these metals will have a large impact on the renewable energy industry.

It is difficult to estimate the demand for renewable energy technologies for metals used in lithium-ion batteries for electric vehicles and storage, as lithium-ion batteries are also used in many other applications. Lithium-ion batteries for all uses make up a large share of the demand for key materials, consuming 40% of cobalt and 37% of lithium in 2016. Nickel demand for batteries is currently only a small share (~3%) of class 1 nickel demand.[124]

Electric vehicles and battery storage are only about 10% of the end-use for lithium-ion batteries in 2018, the remaining 90% of battery demand is for electronics and machinery. However, it is renewable energy technologies that are driving growth in battery production, and the demand from electric vehicles and storage could be 80% of the battery market by 2020, and more than 90% by 2025.[125]

Currently 80% of the cobalt that is used in batteries is used by lithium cobalt oxide (LCO) batteries, which are used in small electronics such as mobile phones and laptops. 17.5% is used in NMC batteries and 2.5% in NCA, both of which are used for electric vehicles and storage, as well as other applications.[126]

Based on this, batteries for renewable energy are likely to be have a current share of between 4 and 8% of total cobalt demand, and similar for lithium[127]. With the current fast growth in battery production for electric vehicles and storage, it is predicted that lithium-ion batteries could reach 54% of cobalt end-use by 2020 and 63% of lithium end-use. If batteries for EVs and storage are 80% of the lithium-ion battery market by 2020, this could mean up to 43% of demand for cobalt in 2020 is for renewable energy. For lithium this could be even higher, with renewable energy technologies using 50% of lithium in 2020.[128]

PV panels use approximately 9% of the total global demand for silver, and 15.7% of industrial demand (excluding coins, bars, jewellery and silverware). PV is one of the largest drivers of demand for silver, and there was a large growth in demand for PV of 19% from 2016 to 2017.[129]

Thin-film panels are a major end-use for tellurium, with approximately 40% of consumption used in CdTe panels. CIGS panels are also a significant share of the consumption of gallium (17%) and indium (8%).[130] The share of cadmium and selenium for thin-film PV is unknown.[131]

For neodymium and dysprosium, it is estimated that approximately 32% of each metal is used in wind turbines and vehicles, split evenly between the two technologies.[132]

For the remaining metals, aluminium, copper and manganese, renewable energy technologies are a very small share of end-use.[133] An overview of the differences between metals is shown in Table 16.

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[124] Energy Insights by McKinsey, 2018. Metal mining constraints on the electric mobility horizon. Available at: https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/

[125] Energy Insights by McKinsey, 2018.

[126] Castellano, R., 2017. How to minimise Tesla's cobalt supply chain risk, Seeking Alpha. Available at: https://seekingalpha.com/article/4113417-minimize-teslas-cobalt-supply-chain-risk

[127] Note it is difficult to estimate total share of cobalt and lithium for renewable energy technologies as all data is either for electric vehicle and storage share of total lithium-ion batteries or the metal share of total lithium-ion batteries, and there is a range of chemistries used with different amounts of lithium and cobalt for the various technologies.

[128] Energy Insights by McKinsey, 2018.

[129] The Silver Institute and Thomson Reuters, 2018. World Silver Survey 2018. Available at: https://www.silverinstitute.org/wp-content/uploads/2018/04/WSS-2018.pdf

[130] Redlinger, M., Eggert, R. and Woodhouse, M., 2015. Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules. *Solar Energy Materials and Solar Cells*, 138, pp.58-71.

[131] U.S. Geological Survey (USGS), 2018, Mineral commodity summaries 2018: U.S. Geological Survey. Available at: https://minerals.usgs.gov/minerals/pubs/mcs/

[132] Du, X. and Graedel, T.E., 2011. Global rare earth in-use stocks in NdFeB permanent magnets. *Journal of Industrial Ecology*, 15(6), pp.836-843.

[133] U.S. Geological Survey (USGS), 2018, Mineral commodity summaries 2018: U.S. Geological Survey. Available at: https://minerals.usgs.gov/minerals/pubs/mcs/

4.4 Supply chain criticality

The criticality of a metal is a measure of the security of its supply chain, including supply risks and likelihood of supply restriction. In this section we review the criticality of the key metals for all end-uses, not specifically for renewable energy technologies. This is an important consideration as metals that have a high level of criticality for all uses are vulnerable for possible supply restrictions or risks, even if renewable energy and storage technologies are not a main consumer of the metal.

Criticality also considers the importance and substitutability of metals. If metals are of high importance, or not able to be substituted, this will make it harder to shift supply for clean technologies from other end uses. Criticality is dynamic over time in response to changes in technology and geopolitics. The degree of criticality is not static between corporations or nations, but varies depending on who it is assessed for, and changes over time in response to technology and geopolitics.[134]

Criticality can be measured in various ways, and in Table 16 we have shown the ratings of criticality based on two established methodologies from Yale University[135] and the European Commission.[136]

Based on these methods, Indium is considered critical by both methodologies, Cobalt, Gallium, Rare Earths in the EU methodology and Silver in the Yale methodology.

Table 16: Summary of supply-side risks

	Concentration of producers	Concentration of reserves	Supply chain criticality	Renewable energy share of use
Aluminium	China 54%	Australia 20%	Low criticality	unknown
Cadmium	China 36%	unknown	Medium criticality	unknown
Cobalt	DR Congo 58%	DR Congo 49%	Critical (EU)	43% (2020)
Copper	Chile 27%	Chile 22%	Low criticality	unknown
Gallium	unknown	unknown	Critical (EU)	17%
Indium	China 43%	unknown	Critical (Yale & EU)	8%
Lithium	Australia 43%	Argentina 18% (resources)	Low criticality	50% (2020)
Manganese	South Africa 33%	South Africa 29%	Low criticality	unknown
Nickel	Indonesia 19%	Brazil 16%	Low criticality	3%
Rare earths	China 81%	Russia/Vietnam 18%	Critical (EU)	32%
Silver	Mexico 22%	Peru 18%	Critical (Yale)	9%
Selenium	China 28%	China 26%	Medium criticality	unknown
Tellurium	China 67%	China 21%	Medium criticality	40%

134 Ciacci, L. et al., 2016a. Metal Criticality Determination for Australia, the US, and the Planet—Comparing 2008 and 2012 Results. *Resources,* 5(4), p.29. Available at: http://www.mdpi.com/2079-9276/5/4/29.
135 Graedel, T.E. et al., 2015. Criticality of Metals and Metalloids. *Proceedings of the National Academy of Sciences*, 112(14), pp.4257–4262. Based on ratings for supply risk and risk of supply restriction.
136 European Commission, 2017, Study on the review of the list of critical raw materials. Available at: https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en

Aside from quantitative measures of criticality discussed above, we have also reviewed qualitative aspects of the supply chain, and the potential for supply disruptions.

Several metals are mined as a by-product, including cobalt (with the exception of artisanal mining in DR Congo), gallium and indium. These make these metals more vulnerable to price changes in these markets, as typically only a small percentage of the revenues of the companies which mine these metals come from the by-product.

There are known examples of supply restrictions for key metals in the supply chain of renewable energy technologies. Global cobalt markets have been impacted by supply restriction in DR Congo during civil unrest. In particular the “cobalt crisis” had a short but significant impact on manufacturing during 1978, and at that time DR Congo (then called Zaire) controlled a similar high proportion of current supply as it does now (around 50%).[137]

There is also the well-known example of China cutting the exports of rare earths to Japan in 2010 in response to a territorial dispute. This led to global prices soaring in the short term and investment in new mining companies, however supply was not as restricted as thought and prices then plunged leaving many new market entrants in financial trouble. Although real supply was only minimally impacted, as there were difficulties enforcing the export cuts, it had economic costs. The market also adjusted and new mines in development prior to the 2010 export cuts in the US and Australia began to supply the market. This action undermined China’s leverage in the market, and it is likely that China’s domination of the rare earth market will continue to steadily decline.[138]

While lithium is not considered critical due to the high resources, the market is relatively opaque for lithium as most lithium is sold in private transactions and there is no benchmark price or futures’ market (unlike other key battery materials). As such the security of lithium supply has become a top priority for global battery and EV manufacturers, leading to the establishment of alliances and joint ventures between manufacturers and mining companies.

[137] Alonso, E. et al., 2012. Evaluating Rare Earth Element Availability: a Case with Revolutionary Demand from Clean Technologies. *Environmental Science & Technology*, 46, pp.3406–3414.
[138] Gholz, E., 2014., Rare Earth Elements and National Security. Council on Foreign Relations. Available at: https://cfrd8-files.cfr.org/sites/default/files/pdf/2014/10/Energy%20Report_Gholz.pdf

5 Environmental and social impacts of supply

The most significant environmental, health and human rights impacts that have been observed in the mining of key metals are outlined below. However, it is important to note that these metals have complex supply chains and many end-uses, so it is difficult to determine direct links to specific industries or companies.

Aluminium

Aluminium metal is predominantly produced from bauxite ores, which are abundant in many regions of the globe. Most bauxite deposits are found close to the surface and are extracted through open-cut mining (also called surface or strip mining), which involves the clearing and removal of large areas of land. The process of excavation, removal of soil and vegetation and transportation can impact ecosystems and lead to air, water and soil pollution.[139] Of particular concern is the release of fine dust particles, which can lead to respiratory and cardiovascular health problems.[140]

The impacts of bauxite mining have been reported in Indonesia, Malaysia, India and Guinea. Indonesia was one of the largest producers of bauxite and China's largest supplier, until production dramatically reduced in 2014 following a ban on the export of unprocessed bauxite. Many Indonesia companies then shifted into Malaysia and mining rapidly increased in the Kuantan region, including many unlicensed mines.[141] The mining occurs close to villages and agricultural land, which have been affected by dust and water pollution.[142] Bauxite mining grew from 200,000 tonnes in 2013 to 35 million tonnes in 2015, until the government banned exports in early 2016 due to environmental concerns.[143]

In the Boké region of Guinea, where bauxite mine has tripled since 2015, communities also face issues from dust in villages and crop fields. Farmlands have been appropriated without adequate compensation and mining has reduce community access to water. [144]

In eastern India, bauxite mining has been controversial for many decades, with many projects delayed or cancelled because of potential environmental impacts and protests. For example, the proposed mine in the Niyamgiri Hills in southern Orissa has been rejected by the government on multiple occasions, including in 2010 and 2014, because of the impacts on the livelihoods of the Dongria Kondh tribe which consider the hill sacred, but disputes with the mining company continue.[145]

Bauxite is processed into alumina and then into aluminium. The production of aluminium is highly energy intensive compared to other common metals such as steel, copper and nickel. Recycling of aluminium can create an energy saving of 95%.146 However, if wastes are not disposed without treatment they can alter the pH of water bodies, making it toxic to aquatic organisms.[147]

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Cobalt

The mining of cobalt in DR Congo impacts the local environment and the health of miners and residents in the surrounding communities. The border between Zambia and the DR Congo, known as the African Copperbelt, is considered one of the top ten most polluted areas in the world.[148] The full extent of environmental impacts is unknown, however the discharge of pollutants from mines and smelters has led to heavy metal contamination of air, water, soil and plants with heavy metals, resulting in severe health impacts.[149]

Cobalt is primarily produced as a co-product of nickel or copper mining. In the DR Congo it occurs alongside copper mining, and the copper-cobalt oxides are particularly suited for lithium-ion battery manufacturing.[150] Cobalt is mined in industrial large-scale mines (LSM), owned by local, Canadian, Australian, European and Chinese companies, as well as artisanal and small-scale mines (ASM). Both types of mines, as well as local smelters, contribute to environmental pollution.[151]

There are approximately 110,000 to 150,000 artisanal cobalt miners in DR Congo.[152] Previous estimates of suggested 60-90% of cobalt exported from the DR Congo was from ASM,[153] but newer estimates suggest 15-20%.[154] Artisanal miners are particularly exposed to heavy metals including cadmium, cobalt, arsenic, lead and uranium, and the concentrations of cobalt found in people living in the area are the highest reported.[155] The local community are also exposed through pollution of soil and water in the food chain and dust inhalation.[156] The long-term consequences are not known but a recent study has found DNA damage in children[157], and a high prevalence of rare birth defects have been reported in regions with heavy mining.[158]

The human rights impacts of cobalt mining include poor working conditions in LSM and ASM mines, and extensive child labour. Artisanal miners work in hand-dug tunnels deep underground without adequate safety equipment, and face a constant risk of cave-ins or landslides, particularly in the rainy season, and suffocation or drowning.[159] Artisanal miners often illegally mine in concessions owned by large companies, or from tailings, as the areas that they previously mined were granted to foreign mining companies in the early 2000s.[160]

Child labour is widespread and it is estimated that there are around 40,000 children under 15 years of age working in artisanal cobalt mines, often doing tasks including sorting, washing and transporting ores.[161] This work is particularly dangerous to children, and they are at risk of physical abuse and financial exploitation. Artisanal miners sell their cobalt to local trading houses, and usually are not able to negotiate a fair price. Despite this, artisanal workers earn higher wages than average, and artisanal cobalt mining provides income to a significant share of the population in the region.[162]

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Copper

The main environmental impacts of copper mining are the contamination of agricultural soils with heavy metals, including copper, lead, cadmium and zinc, and long-lasting water pollution. There is historical contamination of agricultural soils in Chile, the largest copper producer.[163]

Residents in the major copper mining region of China in Jiangxi Province are exposed to copper contamination of agriculture soils and food,[164] and copper mining has led to heavy metal contamination of surface water in Tibet.[165] Risks of heavy metal contamination in agricultural soils have also been observed in India[166] and communities have been exposed to cadmium and arsenic in drinking water in Brazil.[167]

Documented impacts on health of workers include pulmonary tuberculosis (PTB) among underground miners exposed to silica in Zambia[169] and exposure to arsenic for smelter workers in China.[170]

Copper mining has also had significant impacts in North America. A review of 14 copper porphyry mines in the US (accounting for nearly 90% of US production) found the mines were often associated with water pollution from acid mine drainage and accidental releases of toxic materials.[171] All of the mines reviewed had experienced at least one accidental failure, with most mines experiencing multiple failures, such as pipeline spills, tailings failures, or mine seepage. These resulted in a variety of environmental impacts, such as contamination of drinking water aquifers and loss of fish and wildlife. Impacts can be so severe that acid mine drainage can lead to long-term water pollution.

The proposed Pebble mine in southern Alaska would be the largest copper porphyry mine if constructed. The mine is opposed by more than 80% of the Native Alaskan population, as well as many commercial fishers, with fears that the mine could damage the world's largest salmon sockeye fishery.[172] The US EPA tried to impose restrictions on the mine in 2014 because of these potential environmental impacts, but these have been put on hold.

The storage of tailings can help to reduce acid mine drainage, as has been proposed at the Pebble mine. However the breach of tailings dams, the most common source of mining accidents, can have catastrophic environmental effects. For example, the breach of a tailings dam at the Mount Polley gold and copper mine in British Colombia in Canada in 2014 led to the release of 4.5 million cubic metres of mine waste into nearby forest.[173]

Lithium

Lithium production is widely considered to have lower adverse environmental impacts than other battery materials, such as cobalt and nickel. However, it is not without impacts, and mining of lithium from hard rock in Australia and China produces large quantities of waste rock and uses large amounts of water and energy.[174]

Freshwater contamination and water shortages are the main environmental concerns in the 'lithium triangle' between Argentina, Bolivia and Chile.[175] Chemicals used in processing can harm the

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environment if released through leaching, spills or emissions into the air.[176] Mining companies in Chile have been accused of violating rules on the use of water, and companies in Argentina have been fined by the government for environmental offences.[177]

There are also reports of conflicts arising between local communities and mining companies, particularly over water.[178] There are concerns over lack of adequate compensation for affected local communities, with many people remaining in poverty despite decades of lithium mining in Chile, and recently in Argentina.[179]

In the US, several companies are investigating mining lithium in the ecologically damaged Salton Sea in southern California.[180]

Nickel

High purity Class 1 Nickel is most suitable for lithium-ion battery manufacturing, which usually comes from sulphide mines.[181] Mining and smelting of nickel sulphides in Canada and Russia has had lasting environmental impacts, although practices have improved over time in Canada. Environmental impacts include acid rain from the release of sulfur dioxide emissions, heavy metal soil contamination and damage of lakes and wetlands.[182]

Open-cut mining of laterites – which is predominant in the Philippines, Indonesia and New Caledonia – releases large amounts of dust into the atmosphere that can lead to respiratory illnesses and cancer.[183] As some of the highest production from nickel is from these small island nations, there is a risk of toxicity to tropical marine species.[184] Nickel mining in Indonesia has been linked to river pollution[185] and there is conflict with high biodiversity and tourism areas.[186] Nickel mining has been controversial with indigenous Kanak communities in New Caledonia[187] and damaged lagoon ecosystems. [188]

A recently closed nickel refinery in Australia (which processed nickel and cobalt-bearing laterite ores purchased from third party mines in New Caledonia, Indonesia and the Philippines) came under scrutiny for illegally dumping wastewater contaminated with tailings into the Great Barrier Reef World Heritage area.[189] The refinery is set to reopen, based on increased nickel prices due to increased demand, particularly from EV manufacturers.[190]

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Deep sea mining

Deep-sea mining (DSM) generally refers to three types of mining: seafloor massive sulphide deposits around hydrothermal vents, polymetallic nodules (potato sized nodules on the sea floor) and ferromanganese crusts on the seabed surface.[197] These contain a wide range of metals, including silver, gold, copper, nickel, aluminium, manganese, zinc, lithium, cobalt, platinum and rare earths, which in some cases can be found in higher concentrations than on land.[198] For example, more than 120 million tonnes of cobalt have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans and extensive nickel resources.[199]

Mining companies have been interested in deep-sea mining for decades, but it has remained technologically difficult and economically unviable. In addition, environmental concerns and legal uncertainties have slowed development, as well as technical challenges. The growing demand for these metals, including for the renewable energy sector, has led to renewed interest in deep sea mining.

Little is known about the biodiversity and ecosystems of the deep sea, which contains thousands of unknown species that are not found anywhere else on the planet. This makes it difficult to assess the potential impacts of deep-sea mining and put in place adequate safeguards. The potential environmental impacts, including disturbance of the sea floor, the release of sediments and pollution from noise and vibrations, or potential leaks or spills.[200] Sulphide deposits from hydrothermal vents play an important role in climate regulation as a sink sequestering carbon and methane, and there is emerging research which suggests their destruction could lead to the release of sequestered methane with global climate impacts.[201] Deep sea mining is likely to disproportionately impact indigenous people, particularly in the Pacific Islands, and the exploratory phase has already impacted communities in Tonga and Papua New Guinea (PNG).[202]

The Solwara 1 project in PNG, which was to be the first seafloor massive sulphide mine, recovering copper, gold, silver and zinc, has been delayed for many years due to financial difficulties.[203] It is being challenged in court by local communities, who are taking legal action over the consultation process and environmental impacts.[204] Environmental concerns include destruction of seafloor ecosystems, the impact of noise on whales, dolphins, sharks, turtles and tuna, potential for pollution, including on beaches and the seafloor. There are concerns it will pose a risk to customary use, prevent access to fisheries, and lead to a reduction in fish stocks and contamination of seafood. The mine will generate limited revenue and opportunities for employment, and local communities will not receive the same benefits or royalties as a land based mine.[205]

The International Seabed Authority (ISA) has issued 29 exploration contracts in the Pacific, Atlantic and Indian oceans beyond any national jurisdiction,[206] covering an area of more than 1.4 million square kilometres.[207] The regulatory regime requires reform to reflect the latest scientific findings on the importance of the deep sea for biodiversity and climate, and protect local communities.[208]

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205 Rosenbaum, H. 2016, The socio-political and regulatory context for sea bed mining in Papua New Guinea. Available at: http://www.deepseaminingoutofourdepth.org/wp-content/uploads/DSMC-PNG-Report-on-Deep-Sea-Mining.pdf
206 International Seabed Authority*,* 2019, Deep Seabed Minerals Contractors. Available at: https://www.isa.org.jm/deep-seabed-minerals-contractors
207 Miller, K.A., Thompson, K.F., Johnston, P. and Santillo, D., 2018. An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps. *Frontiers in Marine Science*, *4*, p.418.
208 Hunter, J. Singh, P. & Aguon, J. 2018 Broadening Common Heritage: Addressing Gaps in the Deep Sea Mining Regulatory Regime. Harvard Environmental Law Review. Available at: http://harvardelr.com/2018/04/16/broadening-common-heritage/#_ftn61

Rare earths

Rare earths are a group of 15 lanthanides that are found in the same ore deposits, usually at low concentrations, which makes them difficult to extract.[209] The mining and processing of rare earths is complicated and costly, and can create environmental hazards if not managed appropriately.[210] The initial mining stage involves thermal, chemical and physical processes to create a lanthanide concentrate, before mineral extraction processes to separate the rare earth minerals.

Rare earth ores often contain radioactive materials such as thorium (though not as radioactive as uranium mining), and requires large amounts of chemicals to extract the metals.[211] These chemicals, including ammonium bicarbonate and oxalic acid, are potentially harmful if not managed appropriately. The processing of rare earths produces large amounts of waste. For every tonne of rare earth metal, approximately 9,600 to 12,000 cubic metres of waste gas (containing dust, hydrofluoric acid, sulfur dioxide, and sulfuric acid), 75 cubic meters of wastewater, and a tonne of radioactive waste are produced.[212]

Although not well documented, there have been ongoing negative social environmental impacts in China, which at one point was producing 97% of the worlds' supply. The town of Baotou, in Inner Mongolia, processes rare earths from the Bayan Obo mine, a 48 square kilometre open-pit mine that is the largest source of rare earths in China, as well as producing iron ore. Here wastewater from the tailings dams has polluted groundwater, which has led to crop failures and the displacement of farming communities.[213]

Issues around the cost of environmental compliance also led to the closure of the Mountain Pass mine in California in the 1990s, when the mine was sued by the district for wastewater spills. Most recently there have been conflicts over environmental pollution at the Lynas Advanced Materials Plant (LAMP) in Kuantan, Malaysia, which processes concentrate from the Mt Weld mine in Western Australia.[214]

Silver

Silver is primarily mined as a by-product from lead-zinc mines, copper mines or gold mines, rather than as the principal metal at a mine. There are examples of silver mining linked to ongoing water pollution. The Red Dog lead, zinc and silver mine in a remote area of Alaska has been listed as the most "toxics-releasing" facility in the US by the EPA Toxics Release Inventory. The contamination of lead and cadmium in treated mine wastewater flowing into the Red Dog river is a concern for residents of the Native village of Kivalina downstream of the mine.[233] A study of the nearby National Park found elevated concentrations of zinc, lead and cadmium, although this has improved with a large investment in infrastructure to control dust from the mine sites and transport.[234] The largest primary silver mine in the US is the Greens Creek silver mine in Alaska, which is located in an environmentally sensitive area, and is ranked second after Red Dog in the Toxics Release Inventory.[235]

[209] Kuan, S.H., Saw, L.H. and Ghorbani, Y., 2016., A review of rare earths processing in Malaysia. Universiti Malaysia Terengganu International Annual Symposium on Sustainability Science and Management (UMTAS2016)
[210] Hurst, C. 2010, China's Rare Earth Elements Industry: What Can the West Learn? Institute for the Analysis of Global Security (IAGS)
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[214] Ali, S.H., 2014. Social and environmental impact of the rare earth industries. Resources, 3(1), pp.123-134.
[233] Nobel, J. 2018, America's Most 'Toxics-Releasing' Facility Is Not Where You'd Think, *National Geographic,* 21 February 2018. Available at: https://news.nationalgeographic.com/2018/02/most-toxic-town-us-kotzebue-alaska-red-dog-mine/
[234] Neitlich, P.N., Ver Hoef, J.M., Berryman, S.D., Mines, A., Geiser, L.H., Hasselbach, L.M. and Shiel, A.E., 2017. Trends in spatial patterns of heavy metal deposition on national park service lands along the Red Dog Mine haul road, Alaska, 2001–2006. *PloS one*, *12*(5), p.e0177936.
[235] United States Environmental Protection Agency, 2018, 2016 TRI Factsheets: State – Alaska. Available at: https://iaspub.epa.gov/triexplorer/tri_factsheet.factsheet_forstate?&pstate=AK&pyear=2016&pParent=NAT

Mercury was previously used in silver production, which has led to historical contamination of soils in Mexico, Peru and Bolivia. Communities in Peru are exposed to some of the highest levels of mercury contamination worldwide.[236] Concerning levels of mercury has been found in children's blood in Mexico[237] and contamination of groundwater with arsenic and other heavy metals.[238]

The world's second-largest silver mine (Escobal) in Guatemala is currently closed following the constitutional court ruling that the Xinca Indigenous peoples had not been adequately consulted before a mine licence was granted.[239]

Specialty PV metals

For many of the elements used in small amounts in solar PV, little is known about the environmental or human health impacts. However, indium and gallium are known to be hazardous and there are reports of potentially fatal lung disease from exposure to indium particles in manufacturing.[240] Selenium, cadmium and tellurium, which are usually recovered as by-products from other mining processes, are also known to be harmful to human health.[241] These metals are unlikely to cause harm once embedded in the technology, and as they are usually by-products, if they were not extracted in the mining process they would likely remain in tailings.

Impacts of recycling

Recycling is also not without social and environmental impacts. In particular, the recycling of PV panels requires environmentally sensitive chemical processes to extract the metals. The recycling of rare earths from end-of-life products involves similar chemical techniques as are used for raw material processing.[242]

The informal recycling of e-waste occurs in many developing countries, with health risks to workers and environmental pollution. E-waste is considered hazardous waste, and is therefore illegal to export under the Basel Convention.[243] However e-waste is brought in as second-hand devices through legal channels, or illegally imported, as well as collected domestically. Informal workers are involved in all parts of the supply chain, including collection, dismantling and metal extraction.[244]

The working conditions are extremely hazardous, and workers extract valuable metals by hand, using acids and burning off plastics. These processes may not recover the same amount of materials that could otherwise be recovered, and can emit dangerous toxins, heavy metals and acid fumes into the surrounding environment. Workers usually come from marginalised groups, including minorities and migrants, and are not able to negotiate fair pay.

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236 Robins, N.A., Hagan, N., Halabi, S., Hsu-Kim, H., Gonzales, R.D.E., Morris, M., Woodall, G., Heine, P., Zhang, T., Bacon, A. and Vandenberg, J., 2012. Estimations of historical atmospheric mercury concentrations from mercury refining and present-day soil concentrations of total mercury in Huancavelica, Peru. *Science of the Total Environment*, *426*, pp.146-154.
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239 Jamasmie, C. 2018. Guatemala delays ruling on Tahoe's Escobal mine reopening. *Mining.com* http://www.mining.com/guatemala-delays-ruling-tahoes-escobal-mine-reopening/
240 White, S.J.O. and Shine, J.P., 2016. Exposure potential and health impacts of indium and gallium, metals critical to emerging electronics and energy technologies. *Current environmental health reports*, *3*(4), pp.459-467.
241 U.S. Geological Survey (USGS), 2018, Mineral commodity summaries 2018: U.S. Geological Survey. Available at: https://minerals.usgs.gov/minerals/pubs/mcs/
242 McLellan, B. C., Corder, G. D. and Ali, S. H., 2013. Sustainability of rare earths—an overview of the state of knowledge. *Minerals* 3(3): 304-317.
243 See more details at: www.basel.int
244 International Labour Office (ILO) 2014, The informal economy of e-waste: The potential of cooperative enterprises in the management of e-waste. International Labour Office, Sectoral Activities Department (SECTOR), Cooperatives Unit (COOP), Geneva4

Impacts of metal recycling compared to mining

Mining is a large consumer of energy, and the extraction and primary processing of metals is responsible for 10% of global climate change impacts.[245] The mining of lower-grade ores as metals become scarcer could have a significant influence on energy consumption. Recycling has significant energy and greenhouse gas (GHG) emissions savings compared to primary metals. For example, producing 100,000 tonnes of recycled aluminium, nickel or copper saves 92% 90% and 65% of CO^2 emissions respectively. Recycling avoids the creation of waste and potential environmental impacts. It also avoids the large volumes of waste associated with primary extraction; for example, 3.2 tonnes of mud is produced for every tonne of aluminium.[246]

Recycling rates remain low for many metals, as primary metals are often low cost and relatively abundant. The material value and cost of collection must be high enough to justify the cost of recycling, or appropriate policy and industry incentives in place.[247]

Summary of environmental and social impacts

If not managed appropriately, there are significant environmental and social impacts associated with the mining and processing of metals used for renewable energy and technologies. These include pollution of water and agricultural soils through the release of wastewater and dust, the risk of tailings dam failures and health impacts from workers and surrounding communities.

It should also be noted that mining can bring positive economic benefits, for example nickel mining is the largest employer in New Caledonia and makes a significant contribution to the country's GDP.[248] Increased renewable energy may lead to less impacts from coal mining, which is responsible for the greatest number of fatalities, health and environmental issues, including damage of lungs from exposure to coal dust[249] and kidney disease from the contamination of groundwater.[250]

With the growing demand for these metals from renewable energy, responsible mining and recycling practices are necessary to avoid negative environmental impacts and ensure the respect human rights and guarantee an equitable sharing of benefits.

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6 Industry responses and awareness

The following section highlights the current levels of industry awareness and responses. It is based on interviews with seven industry experts, including manufacturers, researchers and NGOs engaged in solar PV, batteries and EVs, mining and recycling, as well as a review of the literature.

The renewable energy industry is very aware of issues around supply risks for key metals. The main concern of the industry is the ability to guarantee long-term supply of key metals at a stable price, rather than a concern over supply restrictions or long-term sufficiency of supply. The industry experts interviewed for this project noted that the solar PV industry are concerned about the price for silver, and that the battery and EV industry see cobalt and nickel as difficult to obtain but are not concerned with long-term supply compared to reserves, especially for lithium.

6.1 Reducing demand through efficiency, substitution and recycling

Current industry responses:

The renewable energy industry has made significant improvements to the efficiency of technologies, to improve performance, minimise demand for materials and reduce production costs. This has a benefit to reducing supply risks, although in most cases this is not the main driver.

The battery industry has been focused on improving the material efficiency of lithium-ion batteries which have significantly improved in efficiency and reduced in cost, dropping 24% in cost from 2016 to 2017.[251] Battery manufacturers have reduced the amount of cobalt in batteries, however the low-cobalt chemistry has a higher nickel content that has increased nickel demand, and a further shift towards cobalt-free lithium-sulfur batteries would increase lithium demand.[252] EV manufacturers are also developing motor technologies that replace neodymium and dysprosium with lower cost rare earths or different materials altogether.[253]

The industry experts interviewed noted that secondary supply would be an important source for manufacturing in addition to primary supply. At this early stage of deployment there is not yet a large volume of these technologies that have reached “end-of-life” and current recycling infrastructure remains underdeveloped and/or not optimised for high value metal recovery. The wider application of lithium-ion batteries is driving advances in recycling and the industry is very aware of the looming volumes from EV. Recycling of lower-value metals from wind turbines relies on existing scrap recycling so it is comparatively mature (excluding rare earth permanent magnets). PV recycling is demonstrated but not optimised for high value metal recovery. These are either industry-led schemes (such as EV battery take-back schemes) or part of regulatory requirements in major markets (such as the EU).

The main driver for industry-led take-back and recycling schemes is corporate responsibility and capturing the economic value of materials, whereas ensuring supply of materials appears to be a secondary motivation, according to interviewees. In the EU, the regulations are also driven by a motive to ensure security of resources for European industry. Safety concerns around fire risk has also provided a driver for managing end-of-life batteries that are used in a broader range of applications than EVs and stationary storage.

Producer responsibility is emphasised in the EU where PV panels have recently been incorporated under the existing Directive for WEEE, and all end of life EV and stationary batteries must be taken-back by the producer under the EU Battery Directive.

[251] Chediak, M., 2017, The Latest Bull Case for Electric Cars: the Cheapest Batteries Ever, Bloomberg, 6 December 2017 https://www.bloomberg.com/news/articles/2017-12-05/latest-bull-case-for-electric-cars-the-cheapest-batteries-ever
[252] Energy Insights by McKinsey, 2018. Metal mining constraints on the electric mobility horizon. Available at: https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/
[253] Widmer, J.D., Martin, R. and Kimiabeigi, M., 2015. Electric vehicle traction motors without rare earth magnets. *Sustainable Materials and Technologies*, 3, pp.7-13.

PV stewardship in the European Union and United States

In the EU, where much of the early deployment was located, PV manufacturers founded PV CYCLE in 2007 as a voluntary scheme focussed on end-of-life management of panels. In partnership with European regulators and contracted service providers, this initiative established 300 collection locations, waste transport and recycling services for panels. PV CYCLE has subsequently been restructured with emergence of new regulations under the EU WEEE Directive. As of December 2017, PV CYCLE had collected and treated 17,000 tonnes of panels and is developing approaches for refurbishment and is currently working to establish activities outside of Europe with interests in USA, China, India and Australia.[254]

In 2012, the EU Waste Electrical & Electronic Equipment (WEEE) Directive was revised to specifically include end-of-life management of PV panels.[255] The approach taken in the WEEE Directive is one based on the Extended Producer Responsibility (EPR) principle that means that producers are liable for the costs of collection, treatment and monitoring. The WEEE Directive sets minimum requirements that member states can adjust (up) when they transpose the requirements into their own legislation. From 2018 onwards the WEEE Directive sets an annual collection target of 65% (by mass) of all equipment put on the market, or 85% of waste generated and an annual recycling and recovery target of 85% recovered, with 80% prepared for reuse or recycling.

Washington State passed legislation in July 2017 to promote sustainable, local renewable energy industries, through modifications to renewable energy system tax incentives and new requirements for PV module recycling[256]. As part of this legislation, the Solar Module Stewardship and Takeback Program was announced, which aims to ensure the recycling of PV modules in a convenient and environmentally sound way. Guidance developed by the State will stipulate how manufacturers placing PV modules on the market must prepare and submit a stewardship plan. The plan will specify the funding mechanism to cover costs of collection, management and recycling, and guarantee that PV modules can be delivered to take-back locations without cost to the owner. Enforcement will begin in January 2021 and applies to all modules purchased after July 1 2017. From this point only manufactures with approved stewardship plans will be permitted to sell PV modules in the State. Non-complying manufactures may be required to pay a penalty of $10,000 for each sale after receipt of a written warning. Washington State is the first US state to have developed this policy approach.

Challenges to recycling:

Whilst recycling can help to offset primary material demand through recycled sources, there are technological, social and environmental challenges to increase recycling rates. In many places collection systems and infrastructure is not well established.

Collection remains a challenge for distributed rooftop PV and storage systems. Installations of solar PV and wind at utility scale are the easiest to facilitate recycling at end-of-life, and auto-manufacturers also have established networks to return batteries through auto-dealerships.

Across all technologies there is a trend for recycling to prioritise the recovery of valuable or problematic materials, and not all metals are being recovered in the process. The main focus of recycling for PV is glass, aluminium, steel and copper, while silver and other specialty metals are not recovered.[257] For lithium-ion batteries cobalt and nickel are the main driver of recovery, and lithium and manganese are not generally recovered.[258] As demand increases the economic drive to recover these metals may justify recovery.

The value of cobalt and nickel drive lithium-ion battery recovery, and recycling is undertaken by manufacturers as well as third-party businesses. However, in many cases the costs associated with collection, sorting and transport make it unviable at current low collection volumes. For solar PV third-party businesses are not usually economic without regulations in place that require recycling,

[254] More details available here: http://www.pvcycle.org/
[255] Directive 2012/19/EU. More details available here: http://ec.europa.eu/environment/waste/weee/index_en.htm
[256] More details available here: https://ecology.wa.gov/Waste-Toxics/Reducing-recycling-waste/Solar-panels
[257] Weckend, S.; Wade, A.; Heath, G. End-of-Life Management Solar Photovoltaic Panels; International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems: Paris, France, 20
[258] King S, Boxall NJ, Bhatt AI (2018) Australian Status and Opportunities for Lithium Battery Recycling. CSIRO, Australia

such as in the EU. This highlights the importance of regulation and product stewardship schemes for batteries and solar PV.

The business model is challenging for solar PV, owing to technological difficulties in recycling with low environmental impact and low cost and the long lifetime of solar PV panels. PV and ancillaries (inverters and batteries) are expected to represent a very large fraction of total e-waste in the coming decades when early installations reach end-of-life.

This highlights the importance of regulations, including standards for high-value recycling. The EU is currently developing technical treatment standards with the aim of promoting ‘high-value’ recycling. These standards will focus on avoiding potentially harmful substances, capturing rare materials (e.g. silver, tellurium and indium) and the quality of recycled material.[259]

Leasing of batteries for EVs

Renault is applying circular economy principles to extend the life of their EV batteries – customers can purchase new EVs and hire the battery. In theory, this novel business model, whereby Renault maintains ownership of the battery provides an incentive to extend the life of the battery and maximise recovery at the end of the EV battery service life. Customers pay a monthly fee based on their requirements and Renault guarantees battery performance to at least 75% otherwise they will repair or replace it. Renault, in partnership with Connected Energy and Power Vault, is also involved in a number of projects demonstrating the potential to reuse vehicle batteries for stationary energy applications when the charge capacity falls below an acceptable level (75 %) for transport applications.[260]

Closed-loop recycling integrated into manufacturing

There is an advantage for manufacturers in establishing take-back and recycling schemes as they can be integrated with the manufacturing process in a closed-loop system. First Solar, the leading manufacturer of CdTe panels, have an in-house recycling process, which also recycles scrap from manufacturing line and any breakages. The company mainly focuses on developing and supplying panels for large utility-scale projects. These projects are an advantage for recycling as they are installed with a decommissioning plan in place, with requirements for recycling.[261]

In Tesla’s recycling program, working components (including case and electronic components) are extracted for reuse or remanufacturing, and the rest of the battery is recycled.[262] Tesla are aiming to create a closed-loop system where batteries can be recycled in the same factory where the materials can be reused in new battery manufacture.[263]

[259] See more details at: http://ec.europa.eu/environment/waste/weee/standards_en.htm
[260] See more details at: https://www.renault.co.uk/renault-finance/battery-hire.html and https://group.renault.com/en/news/blog-renault/renault-optimizes-the-lifecycle-of-its-electric-vehicle-batteries/
[261] See more details at: http://www.firstsolar.com/en-AU/Modules/Recycling
[262] See more details at: https://www.tesla.com/en_AU/blog/teslas-closed-loop-battery-recycling-program
[263] Forfar, J. 2018. Tesla's Approach to Recycling is the Way of the Future for Sustainable Production, Medium, 7 August 2018 https://medium.com/tradr/teslas-approach-to-recycling-is-the-way-of-the-future-for-sustainable-production-5af99b62aa0e

6.2 Securing responsible sources of supply

Current industry responses:

The security of supply of cobalt and lithium supply has become a top priority for global battery and EV manufacturers. This has led to the establishment of alliances and joint ventures between manufacturers and mining companies. The battery and EV industry are signing long-term contracts with miners, often at a price below current market rates.[264] In looking to secure supply of cobalt, many manufacturers are looking to areas of "low sovereign risk" such as Canada or Australia, rather than trying to source responsibly from the DR Congo.

The industry experts interviewed noted that reducing the environmental and social impacts of supply is not a major focus of the renewable energy industry. However, the impacts of cobalt mining in DR Congo are well known to the battery and EV industry.

Amnesty International has undertaken an assessment of 29 companies to assess the extent to which companies have put in place human rights due diligence measures for their cobalt supply chain, to know where their cobalt comes from, and the conditions it was extracted in. They assessed Zhejiang Huayou Cobalt Co., Ltd (Huayou Cobalt), whose wholly owned subsidiary in the DR Congo, Congo Dongfang International Mining SARL (CDM), is known to be major buyer from traders of artisanal cobalt. They also assessed companies that have possible supply chain links to Huayou Cobalt, directly or indirectly, including cathode and battery cell manufactures, electronics companies and EV manufacturers.[265]

The Amnesty International report identified that although some companies have made progress, more action is needed to address human rights risks. The best performing EV manufacturers were BMW Group and Tesla, and the two Korean battery cell manufacturers Samsung SDI and LG Chem have also made progress. However, cathode material manufacturers (based in China and South Korea) are failing to take action, and are a crucial part of the supply chain.

The Amnesty International assessment found that EV companies have taken less action than consumer electronics companies to undertake due diligence of their cobalt supply chains. The industry experts interviewed also felt that the electronics sector was more engaged in due diligence and responsible certification, but that parts of the renewable energy industry have recently shown interest in demonstrating that they are responsible. For the electronics industry, responsible certification has been applied not only apply to the most valuable or problematic metals (such as cobalt), but also to lower value metals, all the way through value chain. This is likely owing to the fact that consumer electronics companies have received greater public scrutiny over their supply chains, compared to the EV companies which are a comparatively new market for lithium-ion batteries.

Challenges to responsible sourcing:

Transparency in the supply chain remains a challenge, particularly for metals such as lithium that are sold in private transactions.

Although some EV are companies are beginning to engage in responsible sourcing and certification, the industry experts interviewed felt that they are more cautious as they are concerned about getting adequate volumes of supply from responsibly sourced mines. However, if the auto industry makes public commitments to responsible sourcing practices, it will encourage more mines to engage with responsible certification schemes. The benefits for mining companies include preferential purchasing contracts, which may also provide EV manufacturers with security of supply, as well as easier access to finance and avoided costs from litigation.

So far industry led-efforts are dominated by consumer-facing companies, who need to put pressure on their suppliers upstream, including mine operators, smelters, traders and component manufacturers to engage in responsible sourcing.[266]

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[264] Reuters, 2017. What Price Lithium, the Metal of the Future? http://fortune.com/2016/06/06/lithium-price-tesla-metal-future/

[265] Amnesty International, 2017, Time to recharge: corporate action and inaction to tackle abuses in the cobalt supply chain. Available at: https://www.amnesty.org/download/Documents/AFR6273952017ENGLISH.PDF

[266] Amnesty International, 2017, Time to recharge: corporate action and inaction to tackle abuses in the cobalt supply chain. Available at: https://www.amnesty.org/download/Documents/AFR6273952017ENGLISH.PDF

Responsible sourcing initiatives

IRMA Standard for Responsible Mining

The Initiative for Responsible Mining Assurance (IRMA) launched the *Standard for Responsible Mining* and certification scheme in 2018. The standard is a multi-minerals approach designed to meet four principles: business integrity, planning for positive legacies, social responsibility and environmental responsibility. The standard is for the certification of industrial-scale mines, and includes guidance on collaborating with initiatives for responsible small-scale and artisanal mining to ensure that the standard does not result in unintended consequences for ASM. The IRMA standard and certification scheme was developed through a multi-stakeholder process and in collaboration with existing standards and schemes, such as chain of custody standards for single-minerals (e.g. steel and aluminium) and product sectors.[267]

OECD Due Diligence Guidance

The Organisation for Economic Co-operation and Development (OECD) has developed the most widely accepted framework for operating or sourcing minerals from conflict-affected and high-risk areas. The *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (OECD Guidance)* sets out a five-step due diligence process for all companies involved in the mineral supply chain. It is endorsed by states and is widely recognized as the international standard for responsible mineral supply chains.[268] The document also provides guidance on sourcing from artisanal mines and aims to ensure that artisanal mining communities to continue to benefit from mining. The OECD Guidance forms the basis of many of the requirements of IRMA.

Responsible Minerals Initiative (RMI)

The Responsible Minerals Initiative (RMI) has over 350 members, and provides programs and resources to enable companies to conduct due diligence in line with the OECD guidance. The RMI has a specific focus on cobalt and is piloting a reporting tool for companies to map their downstream supply chain.[270]

Cobalt initiatives

There are various initiatives specific to cobalt. The China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters (CCCMC) adopted the *Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains (CCCMC Guidelines)*, which are aligned to due diligence framework in the OECD Guidance. These guidelines apply to all Chinese companies involved in upstream (extraction, trading, transport and processing) and downstream parts of the supply chain.[271] The CCCMC launched the *Responsible Cobalt Initiative (RCI)* in November 2016, which aims to promote corporate supply chain due diligence. It has 16 corporate members, mainly battery cathode and cell manufacturers and downstream electronics companies, but also includes Huayou Cobalt.

The *Cobalt Institute* (CI) is a cobalt industry association which plans to establish industry wide guidance on responsible sourcing.[272] *Drive Sustainability*, which is a group of European auto-manufacturers, have developed a coordinated approach to responsible sourcing. They are working with their suppliers and sub-suppliers to map their cobalt supply chains.[273]

There are a number of other single-mineral certification schemes focused on chain-of-custody along the supply chain. This includes the *Aluminium Stewardship Initiative*, with members including Audi, BMW and Jaguar Land Rover, which has developed a third-party certification program for sustainability and human rights principles in production, use and recycling. *ResponsibleSteel* are currently developing a multi-stakeholder standard and certification initiative for the steel industry.[274]

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[267] See more details at: https://responsiblemining.net/
[268] OECD, 2016. OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk *Areas*, Available at: http://www.oecd.org/corporate/mne/mining.htm
[270] See more details at: http://www.responsiblemineralsinitiative.org/media/docs/RMI/RMI-Cobalt2.pdf
[271] China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters (CCCMC), 2015, Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains (CCCMC Guidelines). Available at: http://www.cccmc.org.cn/docs/2016-05/20160503161408153738.pdf
[272] See more details at: https://www.cobaltinstitute.org/responsible-sourcing.html
[273] See more details at: http://drivesustainability.org/
[274] See more details at: https://www.responsiblesteel.org/draft-standard/

There are a large number of responsible sourcing initiatives, most of which are voluntary and industry-led. If these initiatives are widely adopted, it may lead to more responsible supply chains. However very few jurisdictions have regulations for due diligence of supply chains.

The EU Mineral Due Diligence Regulation and the US Dodd-Frank Act require due diligence and public reporting for tantalum, tin, tungsten or gold supply chains (known as 3TG and often referred to as "conflict minerals") originating from the DR Congo or neighbouring countries.[275] However these are the only metals which they are required to report on. For cobalt specifically, Amnesty International recommend that the Congolese government include cobalt as a "designated mineral", which would mean companies are required to undertake due diligence in the same way as they are required for 3TG metals.

Responsible sourcing initiatives need to ensure that they do not lead to unintended negative consequences, such as increasing poverty, by avoiding sourcing from countries with poorer governance, as has been a criticism of the Dodd-Frank act.[276] Focusing on supporting responsible operations has a better long-term impact than avoiding supply from these countries.

Responsible sourcing will be most effective through verified high-bar standards or certification schemes (such as IRMA) and not solely reliant on industry self-monitoring. The renewable energy transition and associated resource requirements could provide an opportunity for promoting new frameworks for resource governance at the international level.[277]

[275] See more details at: https://www.cftc.gov/LawRegulation/DoddFrankAct/index.htm and https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.130.01.0001.01.ENG&toc=OJ:L:2017:130:TOC
[276] Raghavan, S., 2014. How a well-intentioned U. S. law left Congolese miners jobless. *The Washington Post*.
[277] Ali, S. H., D. Giurco, N. Arndt, E. Nickless, G. Brown, A. Demetriades, R. Durrheim, M. A. Enriquez, J. Kinnaird, A. Littleboy, L. D. Meinert, R. Oberhänsli, J. Salem, R. Schodde, G. Schneider, O. Vidal and N. Yakovleva, 2017. Mineral supply for sustainable development requires resource governance. *Nature* 543: 367.

6.3 Key intervention points going forward

Under a 100% renewable energy scenario metal requirements could rise dramatically. It is expected that with the renewable energy transition, renewable energy technologies will consume a growing share of the metals discussed in this report. This growth in demand will have significant influence on overall market dynamics, including influencing prices, which may feedback to efforts to reduce material intensity and invest in reuse and recycling infrastructure, or promote responsible sourcing.

Importance of recycling to reduce demand

This study found that cobalt, lithium and rare earths have the highest projected demand and supply risks, and batteries for EVs are the main driver of demand for these metals. Modelling the potential to reduce primary demand found that recycling is the most important strategy to reduce demand for battery metals, and materials efficiency has the most potential to reduce demand for solar PV metals. However, as renewable energy and battery manufacturers are already focused on improving the efficiency of material use, overall recycling is the most important strategy going forward for these industries to reduce primary demand.

Need for responsible sourcing

Recycling can reduce demand for primary metals, but as shown in this study, recycled sources from renewable energy and battery technologies cannot meet all demand, and there is a time delay for when recycled metals become available. New mining is likely to take place to meet demand in the short term, and new mines are already under development linked to renewable energy (e.g. cobalt, copper, lithium, rare earths, nickel). When supply cannot be met by recycled sources, responsible sourcing is needed to promote environmental stewardship and the respect of human rights.

Key intervention points along the supply chain to promote recycling and responsible sourcing include:

- **Design:** It is important to consider lifecycle impacts in the design of renewable energy technologies and systems, through consideration of functionality and supply chain impacts of material selection. For example, batteries can be designed for recycling supported through closer collaboration between recyclers and cathode manufacturers. At the system level, transport systems should be designed to minimise the need for batteries, through promoting public/active transport and car-pooling. Alternative technologies such as pumped hydro can be considered for stationary storage.[278]
- **Manufacturing:** The renewable energy and battery industries need to engage publicly with mining and chain of custody standards, to show they are committed to sourcing responsibly and to encourage more mines to engage in responsible certification. There are significant opportunities for sector-based commitments to responsible procurement and supply chain due diligence. As consumer facing brands, which are most likely to face pressure from consumers to act responsibly, EV manufacturers are more likely to be able to create change along the supply chain and influence their suppliers upstream.
- **Purchasing:** Large purchasers of renewable energy and storage technologies, such as energy utilities or governments, have an opportunity to require responsible sourcing and plan for take-back and recycling at end-of-life in their procurement contracts.
- **Use:** Changes in consumption patterns of organisations and consumers, such as shifts towards public transport over private vehicles and increased energy efficiency, is also an opportunity to reduce demand.
- **End-of-life:** Manufacturers, third party businesses, and even some mining companies are involved with the recycling or reuse of technologies at end-of-life. However, policy to ensure take-back and recycling at end-of-life of batteries and solar PV will be needed if the industry does not establish effective voluntary schemes.

The renewable energy transition is an opportunity to promote the stewardship of both primary sources and technologies at end-of-life. As renewable energy technologies become the major driver of demand for key metals examined in this report, this has the potential to improve the sustainability of the supply chain for these metals more broadly.

[278] Florin, N. and Dominish, E., 2017, Sustainability evaluation of energy storage technologies, Report prepared by the Institute for Sustainable Futures for the Australian Council of Learned Academies. Available at: https://acola.org.au/wp/wp-content/uploads/WP3_UTS_full.pdf

Appendices

Energy scenario

Table 17: Reference Scenario

Electricity generation (TWh/ year)	2015	2020	2025	2030	2035	2040	2045	2050
Hard coal (& non-renewable waste)	7,662	8,334	8,942	10,237	11,389	12,495	13,083	13,589
Lignite	1,780	1,767	1,773	1,803	1,832	1,901	1,962	1,982
Gas	5,743	6,179	6,998	8,159	9,294	10,428	11,422	12,285
Oil	877	739	633	512	446	382	330	287
Diesel	122	122	125	131	137	141	148	153
Nuclear	2,545	2,991	3,218	3,452	3,638	3,825	4,018	4,218
Hydrogen	0	0	0	0	1	1	1	1
Renewable H2	0	0	0	0	0	0	0	0
Hydro	3,888	4,299	4,684	5,202	5,583	5,964	6,320	6,667
Biomass (& renewable waste)	471	649	785	953	1,082	1,211	1,354	1,514
Geothermal	80	104	130	178	230	281	344	426
Solar thermal power plants	9	25	38	58	94	130	183	260
Ocean energy	1	2	4	7	16	25	37	53
Wind	838	1,394	1,948	2,431	2,894	3,358	3,856	4,389
PV	247	662	1,057	1,460	1,826	2,192	2,645	3,209
Total renewables	**5,534**	**7,133**	**8,645**	**10,290**	**11,725**	**13,160**	**14,740**	**16,517**
Total generation	24,262	27,266	30,333	34,584	38,461	42,332	45,702	49,032
Share of renewables	**23%**	**26%**	**29%**	**30%**	**30%**	**31%**	**32%**	**34%**

No of vehicles (thousand vehicles)	2015	2020	2025	2030	2035	2040	2045	2050
Battery Electric Vehicles (BEV)	1,074	5,596	12,952	27,619	47,396	72,691	144,325	218,591
Plug-in Hybrid Electric Vehicles (PHEV)	56	441	1,377	3,759	8,326	16,070	28,221	46,683
Commercial Vehicles (CV)	102	432	1,209	3,001	4,800	6,004	7,016	7,480
Buses	184	368	1,061	2,429	4,283	5,991	7,067	7,914
Total electric vehicles	1,416	6,837	16,600	36,807	64,805	100,756	186,628	280,668

Battery capacity (GWh)	2015	2020	2025	2030	2035	2040	2045	2050
Battery Electric Vehicles (BEV)	41	224	557	1,326	2,465	4,143	8,659	13,553
Plug-in Hybrid Electric Vehicles (PHEV)	0	3	11	38	100	209	395	700
Commercial Vehicles (CV)	26	130	423	1,200	2,160	3,002	3,859	4,488
Buses	9	22	61	128	227	311	382	453
Total battery capacity	76	378	1,053	2,691	4,951	7,665	13,295	19,194

Table 18: 1.5 Degree Scenario

Electricity generation (TWh/ year)	2015	2020	2025	2030	2035	2040	2045	2050
Hard coal (& non-renewable waste)	7,638	7,323	4,931	2,164	439	20	0	0
Lignite	1,780	1,609	445	182	80	0	0	0
Gas	5,743	6,245	6,636	5,896	4,879	3,056	1,234	0
Oil	877	737	502	269	43	5	0	0
Diesel	122	103	68	22	0	0	0	0
Nuclear	2,545	2,921	2,250	1,515	841	182	12	0
Hydrogen	0	0	34	278	754	1,719	2,620	3,127
Renewable H2	0	0	16	210	643	1,596	2,547	3,127
Hydro	3,888	4,299	4,495	4,625	4,743	4,823	4,909	4,988
Biomass (& renewable waste)	471	823	1,683	2,395	2,660	2,933	3,156	3,286
Geothermal	80	113	314	908	1,568	2,266	2,848	3,324
Solar thermal power plants	9	32	329	1,834	3,772	5,709	7,211	8,147
Ocean energy	1	2	41	168	414	705	991	1,178
Wind	838	1,545	4,536	9,075	13,677	17,622	20,300	21,567
PV	247	918	3,917	7,483	11,396	15,633	18,439	19,695
Total renewables	**5,534**	**7,732**	**15,331**	**26,699**	**38,873**	**51,286**	**60,402**	**65,311**
Total generation	24,237	26,670	30,180	36,816	45,265	54,672	61,720	65,311
Share of renewables	**23%**	**29%**	**51%**	**73%**	**86%**	**94%**	**98%**	**100%**

No of vehicles (thousand vehicles)	2015	2020	2025	2030	2035	2040	2045	2050
Battery Electric Vehicles (BEV)	1,345	10,158	102,132	284,926	495,630	677,357	772,588	916,469
Plug-in Hybrid Electric Vehicles (PHEV)	85	2,889	55,147	129,023	183,240	158,563	92,885	56,932
Commercial Vehicles (CV)	102	1,333	10,673	40,600	81,416	87,430	90,078	91,248
Buses	184	368	1,061	2,429	4,283	5,991	7,067	7,914
Total electric vehicles	1,716	14,748	169,014	456,978	764,570	929,341	962,618	1,072,563

Battery capacity (GWh)	2015	2020	2025	2030	2035	2040	2045	2050
Battery Electric Vehicles (BEV)	51	406	4,392	13,676	25,773	38,609	46,355	56,821
Plug-in Hybrid Electric Vehicles (PHEV)	0	17	441	1,290	2,199	2,061	1,300	854
Commercial Vehicles (CV)	26	400	3,736	16,240	36,637	43,715	49,543	54,749
Buses	9	29	229	782	1,148	1,354	1,497	1,595
Total battery capacity	87	852	8,797	31,989	65,757	85,740	98,695	114,019