3. Renewable energy transition, demand for metals and resource curse effects¹

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1 INTRODUCTION

Mitigating climate change will require major changes to energy systems. It is widely acknowledged that fossil fuels can affect local and national development pathways, for better or worse. Low-carbon energy systems use renewable energies instead of fossil fuels. With only a few exceptions, renewable energies use flows that are often diffuse and distributed geographically, and renewables are therefore assumed to reduce the risk of a resource curse (Månsson, 2015). The energy transition is framed by some as ‘geopolitical’, as it creates both relative winners and losers, depending on, for example, how natural resource endowments are distributed (Overland et al., 2019; Vakulchuk, Overland and Scholten, 2020). Compared to fossil energy, low-carbon energy technologies contain both more metals and new ones too. Some of these metals are geographically concentrated and found in countries with fragile institutions and high levels of corruption. Policy responses may therefore be required to avoid some of the drawbacks associated with fossil fuels (Ali et al., 2017; Bazilian, 2018; Lee et al., 2020).

The aim of this chapter is to provide an overview of the present state of knowledge of how a renewable energy transition affects metal demand and the risk of a resource curse in mining countries. The chapter starts with an overview of metals that are used in low-carbon energy systems and are perceived as critical. Next, the chapter summarizes insights from the existing literature on the potential metal demand for a renewable energy transition. The final section then turns to the supply side to address from where these resources could come and what impacts this could have for states and local mining communities.

2 LOW-CARBON ENERGY SYSTEMS AND THEIR DEMAND FOR CRITICAL METALS

Renewable energy systems require more materials in total and some different materials than their fossil fuel counterparts. Materials are used in all steps of the supply chain and some metals are used in several steps. To grasp which materials and how much can be required for low-carbon energy transitions, the entire supply chain needs to be analysed. This section there-

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fore provides an overview of metals used in the different steps of the supply chain, starting with production, distribution and storage and then ending with final use.

Each step of the supply chain utilizes different technologies to meet a certain requirement. Solar panels, solar thermal and wind power plants are all examples of renewable energy production technologies that can be used, but they operate on different principles and can require different materials. Each of these groups of technologies also contains different sub-technologies that use different physical principles to convert energy into electricity, and as a result they have different material demands.

The heterogeneity of materials used in different technologies enables substitution, which in turn provides flexibility. Availability of certain elements may therefore not be as critical for specific technologies in the long term as they are in the short term. Also, new technologies may be developed that depend on other physics and material needs. Some of these technologies are known but are currently at the research and development stage, while others are as yet unknown. Markets for technologies and raw materials are dynamic and can incentivize development of new technologies as well as improve the performance of existing ones if some materials become more scarce and costly.

2.1 Renewable Power Production

Renewable low-carbon energy production converts solar inflow or natural flows derived from this, geothermal heat, or potential energy from gravitation such as wave power, into usable forms of energy. Solar photovoltaics (PV) and wind power receive most attention and are often assessed to meet most of the demand in future renewable energy systems (see, e.g., International Energy Agency [IEA]/Organisation for Economic Co-operation and Development [OECD], 2017). This section will therefore focus on the material requirements of these two technology groups.

Solar PV

The most common solar power technique is the first generation of solar PV, containing crystal silicon wafers and silver on the back (Kavлак et al., 2015). Second-generation cells either contain cadmium and tellurium (CdTe) or copper, indium gallium and selenium (CIGS) (Elshkaki and Graedel, 2015). These cells are also referred to as thin film cells and have a multi-crystal structure. Third-generation solar cells – for example, perovskite solar cells and Grätzel cells – are not yet commercialized, but several options are being researched that use metals that are more abundant than current technologies. Silicon is the most abundant element in the earth's crust but requires an energy-intensive and costly process to purify it to PV grade standard. Tellurium, indium and gallium are by-products from extraction of copper, zinc and aluminium, respectively (Nassar, Graedel and Harper, 2015). Most of the global silver production is mined as a by-product, mainly from sulphide lead-zinc ores. The host metal restricts the maximum extraction of the by-product, but current recovery rates are far below the theoretical potential which provide flexibility to expand by-product production (Frenzel et al., 2017).

Wind power

The most common wind power plant designs use non-renewable basic materials such as steel and aluminium in the tower and nacelle, and concrete in the foundations. There are different sub-technologies available for the generator. The two main categories are permanent magnet

(PM) and electrically excited, in terms of material requirements (Viebahn et al., 2015). The PM generator contains a mix of materials including neodymium (a rare earth element with magnetic properties), dysprosium (rare earths that increase the PM's heat tolerance), iron, boron and sometimes praseodymium and terbium (Pavel, Lacal-Arántegui and Marmier et al., 2017). Generators that are electrically excited have copper coils instead of PMs, which make the configuration heavier, increase the size and reduce efficiency at partial load. A gearbox is sometimes also used, which reduces the PMs' weight relative to installed power capacity, but also reduces reliability. PM designs are therefore preferred for offshore installations since maintenance is more costly there than onshore. High-temperature super conductors using yttrium may be used in the future, but much more development is required for this technology to be commercialized (Viebahn et al., 2015).

Other technologies

Concentrated solar power (CSP) uses reflectors to heat up a medium that is then used to propel a turbine connected to a generator. For the generator's material requirement, these technologies use silver in the collector to increase conversion efficiency and some also use nitrate salts ($\text{NaNO}_3 + \text{KNO}_3$) for thermal storage (Pihl et al., 2012). There are several other technology groups that can be part of a renewable power mix. However, these are likely to partly demand similar materials to wind power plants if generators are used to convert kinetic or potential energy into electricity – for example, wave energy. To what extent these technologies are more or less material intensive than wind power will thus partly depend on their respective capacity factor.

2.2 Distribution and Storage

Electrification and grid storage

Some renewable energy production is distributed – for example, solar PV – which limits the need for transmission infrastructure. Other technologies, such as wind power, express economies of scale and require new transmission infrastructure to be constructed so that production can be situated in optimal production localities rather than proximate users. Expanding transmission infrastructure facilitates the integration of variable renewable production, as it helps balance the grid. Investments in such super-grids may require the use of copper in high-voltage direct current (HVDC) cables (Harmsen, Roes and Patel, 2013). Copper is also used in other power electronics, such as fast chargers for EVs.

Storage technologies include grid-connected stationary storage and mobile storage used, for example, in vehicles. Redox flow batteries using vanadium are well suited for use as stationary storage, owing to their competitive cost and because discharge power and energy storage can be designed independently (Stantec, 2018).

Energy storage in vehicles

The two main energy storage technologies expected to be used in electric vehicles are batteries and fuel cells. Lithium-ion batteries are the currently preferred sub-technology as a result of their high energy capacity, power capability and lifetime. A variety of lithium-ion cathode chemistries are in use that contain nickel, manganese and/or cobalt in different proportions (IEA/OECD, 2019). Cathode chemistries are abbreviated according to metals used and their relative proportions. For example, NMC111 contains the same ratio of nickel, manganese

and cobalt. The relatively higher cost of cobalt compared to the other metals has incentivized battery manufactures to reduce its ratio, and newer NMC generations include NMC433, NMC532, NMC622 and the latest NMC811. The main material trade-off is the increased use of nickel to replace cobalt. Lithium batteries that do not contain cobalt (lithium ferrophosphate [LFP] chemistry) have been used in vehicles but their performance (e.g., energy density) has so far been inferior compared to chemistries that contain cobalt. Solid-state batteries that have higher performance than current batteries and do not use cobalt are being researched as well as ion batteries that do not use lithium – for example, sodium-ion batteries (Vaalma et al., 2018).

Fuel cells are used to convert hydrogen and air to electricity and water. Platinum is typically used in the fuel cell as a catalyser and assumed to be used in future hydrogen vehicles (see, e.g., Sun, Delucchi and Ogden, 2011). However, some of the platinum can be replaced by other platinum group elements (PGEs), such as palladium (Antolini et al., 2011). Although many (institutional) barriers exist, hydrogen can also be used instead of coal for direct reduction to produce steel with radically lower emissions than today (see, e.g., Kushnir et al., 2020). This sector may add additional demand for platinum and PGEs.

2.3 Final Use

Increased electrification and energy efficiency can increase demand for some metals. Electric vehicles (EVs), including hybrids, have motors that operate on similar principles as generators in wind power plants and therefore use the same materials: copper (coils) or rare earths (PM) (Pavel, Thiel and Degreif et al., 2017). The combination of higher efficiency at partial and variable load and smaller size makes PM motors particularly attractive in hybrids where engine space is restricted, and the motor complements an internal combustion engine. PMs are also preferred in EVs but electrically excited copper coils have lower cost and have therefore been used as the space is not as limited as in hybrids.

Replacing incandescent light bulbs with light emitting diodes (LEDs) increases energy efficiency but also demand for scarce materials, in particular indium, but also gallium, germanium and some rare earths (europium, terbium and yttrium) (Pavel et al., 2016). Some of these metals are the same as those used in thin-film solar PVs, owing to similarities in optical and semiconducting requirements. Newer LED generations, and those currently being researched, use less and fewer scarce metals than older technologies.

2.4 Overview of Metals and Criticality Status

Fifteen of the metals identified above are summarized in Table 3.1. As can be seen from the table, the United States Department of the Interior classifies ten of these as critical and the European Union eight (EU, 2017; US DoI, 2018). These classifications are continually updated to include more raw materials. The US and the EU have some similarities in selecting criteria for inclusion on the list, such as import dependence, geographical concentration of supply sources and the extent to which substitutes are available, but the lists still differ slightly. For example, the US list is slightly longer as it includes a total of 35 mineral commodities, while its European equivalent includes 27. Adding a resource to the list has implications for natural resource markets, as businesses, government agencies and research funding can then be prioritized to mitigate the supply risk. In Japan, government and businesses cooperate to secure available supplies and reduce price volatility by coordinating procurement and

stockpiling of some raw materials perceived as critical (Japan Oil, Gas and Metals National Corporation [JOGMEC], 2017). One recent study suggested that policymakers should evaluate and include demand for critical raw materials in their climate change mitigation planning, specifically relating to countries' nationally determined contributions (NDCs) (Sovacool et al., 2020). How and why some raw materials are assessed as critical is subject to increasing research interest (Graedel and Reck, 2016; Schrijvers et al., 2020).

2.5 Metal Demand in Energy Transition Scenarios

A number of recent studies have estimated metals requirements for transitioning parts of or the whole global energy system (Watari, Nansai and Nakajima, 2020). Different methodologies have been used, but they all involve estimating current material intensities (i.e., the weight of metal per kilowatt [kW] power or kilowatt-hour [kWh] storage), material intensity learning effects (the rate at which metal intensity declines and its shape), future demand for energy technology groups (e.g., installed wind power capacity) and the composition of sub-technologies within those groups.

Estimates of material intensities vary greatly, partly because of rapid technological development that makes older estimates invalid. Current values are often, but not always, much higher than the theoretical limit and future improvements are therefore highly likely, but their magnitude and pace remain unknown. The composition of sub-technologies is uncertain and can be dynamic, so that if the supply of certain metals becomes restricted and price increases, the composition will change in response. Scenarios are therefore often used to manage the uncertainty inherent in the large number of assumptions that must be made and assess how this impacts the end results. Each scenario combines a normative end state target and explores plausible pathways to reach that target.

Two of the main results derived from these calculations are cumulative material demand for each metal and the respective growth rate. When combined with estimates of material recycling rates, their development and technological lifetimes, this shows how demand for primary metal can change as a result of an energy transition. These estimates can then be compared with current known reserves (i.e., economically recoverable reserves using current technologies and market price), technically recoverable resources and current mining rates. The results indicate whether certain scenarios are unlikely (e.g., when cumulative metal demand is much higher than technically recoverable reserves) and identifies bottlenecks (e.g., if the mining rate must increase rapidly from today's level).

Several conclusions of possible future metal demand and how it relates to reserves, resources and mining growth rates can be drawn, based on previous studies. Not all sub-technologies are scalable, but backstop technologies exist to enable technology groups to scale up (Månberger and Stenqvist, 2018). For example, some thin-film solar PVs use scarce metals, and current metal intensities make it unlikely for these alone to meet future PV demand, but crystalline silicone PVs and third-generation PVs use more abundant materials. Metal scarcity may affect the future market share of different sub-technologies, but it is less likely to constrain the growth of entire technology groups.

Primary demand for many critical metals is likely to grow, and low-carbon technologies can dominate demand for many metals. Some critical metals are produced as by-products, which makes supply less responsive and dependent on host metal supply (Elshkaki and Graedel, 2015). There is room to increase by-product recovery without increased extraction of the host

Table 3.1 *Overview of 15 elements used in low-carbon energy technologies, approximate market price range in the last ten years and criticality classification*

Element	Application(s)	Market Price Range (\$/ton) ^a	Critical According to US ^b	Critical According to EU ^c
Cobalt (Co)	Lithium-ion batteries	30 000–90 000	Yes	Yes
Copper (Cu)	Electrification (production, distribution, storage, use)	5000–10 000	No	No
Dysprosium (Dy)	Motors, generators	360 000–28 00 000	Yes	Yes
Gallium (Ga)	Solar PV, LED	400 000–1 000 000	Yes	Yes
Indium (In)	Solar PV, LED	300 000–600 000	Yes	Yes
Lithium (Li)	Lithium-ion batteries	20 000–90 000	Yes	No
Neodymium (Nd)	Motors, generators	35 000–400 000	Yes	Yes
Nickel (Ni)	Lithium-ion batteries	10 000–30 000	No	No
Platinum (Pt)	Fuel cells	30 000 000–60 000 000	Yes	Yes
Manganese (Mn)	Lithium-ion batteries	2000–4000	Yes	No
Selenium (Se)	Solar PV	22 000–66 000	No	No
Silver (Ag)	Solar PV, solar thermal	55 000–110 000	No	No
Tellurium (Te)	Solar PV	30 000–450 000	Yes	No
Silicon (Si)	Solar PV	15 000–50 000	No	Yes
Vanadium (V)	Redox flow batteries	16 000–160 000	Yes	Yes

Notes and sources:

- a. Approximate price range is calculated for the element using the market price of the traded grade during the last ten years – for example, vanadium market price is based on vanadium content of vanadium pentoxide (V2O5). Price data are from Leader, Gaustad and Babbitt (2019), Månberger and Johansson (2019) and US Geological Survey (USGS) (2019).
b. US DoI (2018).
c. EU (2017).

(Frenzel et al., 2017). However, by-products have low elasticity of supply even when the host supply is not restricted (Fu, Polli and Olivetti, 2018). By-products represent a low share of the product cost and the metal producer's revenue (miner and refiner). Price increases can therefore incentivize additional supply without major increases in the cost of the final product.

Recycling of critical metals has limited impact on short-term primary metal demand but a considerable impact in the long term (Kushnir and Sandén, 2012). This is because recycling rates are currently often low (e.g., only a few per cent for lithium), critical metal demand is increasing rapidly, technologies have long lifetimes (which delays the time until the material can be recycled) and a limited amount of critical metals are to be found in older technologies (Månberger and Stenqvist, 2018). Recycled material can overtake primary material supply in 2050 for many applications if recycling rates increase as metal intensities decline (Månberger and Johansson, 2019). The impact of other circular economy strategies (remanufacturing, reuse and lifetime extension) has received less research attention (Watari et al., 2020).

Demand for several metals is increasing rapidly, according to many studies – for example, dysprosium, neodymium and lithium (ibid.). Two metals used in batteries – lithium and cobalt – are often depicted as the main bottlenecks, both when reserves are compared to cumulative demand and when demand growth rates are compared with current mining rates (Deetman et al., 2018; Giurco et al., 2019; Månberger and Stenqvist, 2018). Cobalt is a short-term bottleneck, as to a large extent it is produced as a by-product (of nickel and copper) and cobalt demand is growing more rapidly than host demand. Some studies show that cobalt reserves are insufficient in the long term, but this should be interpreted with caution, given the available substitutes and the rapidly decreasing cobalt content in newer lithium batteries (Månberger and Stenqvist, 2018). Extractable lithium resources are sufficient to electrify the global road transport system, but current reserves are not. It should be noted that future reserve growth is likely to occur as a result of technological development of extraction techniques, new discoveries and higher prices, but its magnitude is uncertain. Lithium recycling rates are low and must increase for lithium batteries to dominate the road transport sector's demand for energy storage in the second half of the twenty-first century.

There are metal demand trade-offs. Cobalt is increasingly being substituted by nickel in lithium batteries. Nickel resources are an order of magnitude higher than cobalt resources and nickel mining is greater too, which makes supply more flexible, but there are currently not enough refineries to purify nickel to the required battery grade (IEA/OECD, 2019).

Demand for non-fuel minerals increases with higher climate ambition – that is, the 1.5°C target has higher metal requirements than 2°C target as a result of more rapid electrification of the transport sector and penetration of renewable power in the supply mix. This holds both for short-term metal demand (IEA/OECD, 2019) and long-term metal demand (Watari et al., 2019). Rapid electrification of the transport sector doubles its demand in 2030 for lithium, cobalt, copper and nickel compared to a baseline scenario, according to the IEA (IEA/OECD, 2019). However, it should be noted that these studies use quantitative demand modelling techniques and the role of behavioural change and other structural changes required to meet more stringent emission reductions may therefore be overlooked.

Studies of future demand for critical metals in renewable energy systems seldom estimate if and how demand from other sectors can develop (Watari et al., 2020). Studies therefore tend to underestimate aggregate future metal demand. One exception can be found in Deetman et al. (2018), who analyse demand up to 2050 for five metals (copper, cobalt, lithium, neodymium and tantalum) for vehicles, power production and appliances in several climate-mitigation

scenarios. The study finds that appliance demand for neodymium and tantalum can be similar to demand from the power and vehicle sectors. Growth in lithium and cobalt demand is completely dominated by batteries used in EVs. At least 75 per cent of copper is used for vehicles and power production.

3 IMPACTS ON NON-FUEL MINERAL-RICH COUNTRIES

As noted above, it is widely assumed that a renewable energy transition will increase metal demand, but the literature on how this increased demand can affect non-fuel mineral producers is still scarce. On the other hand, a vast literature exists on how fossil fuel (rents) can be a ‘resource curse’ (see, for example, Månsson, 2014). The resource curse hypothesis has several dimensions. One is that resource wealth can reduce development prospects and instead enable undemocratic governments to remain in power. Another is that affected countries have lower economic growth than comparable countries without resource wealth.

Resource conflicts can involve both state and non-state actors that fight for control of and access to resources. Fossil fuel rents from ‘conflict resources’ can be used to finance non-state actors participating in conflicts in poor countries that are rich in resources – that is, countries that have low gross domestic product (GDP) per capita but a high share of their GDP attributed to resource extraction (Basedau and Lay, 2009). A related issue is the infamous ‘Dutch disease’ – that is, the notion that resource extraction can crowd out other sectors of the economy due to currency appreciation, to such an extent that economic diversity is reduced, and the country’s economy becomes sensitive to the produced commodity’s world market price (Corden, 1984).

There are several underlying factors that explain how resources can affect states’ development, such as the geographical concentration of resources, the high economic value compared to the size of the economy, and institutional conditions. These parameters are used here to explore whether metals used for renewable energy can cause a resource curse and identify countries at risk. These insights can be used to mitigate the risk, as resource wealth is not deterministic in causing a resource curse, as demonstrated, for example, by Norway’s development and its successful approach in establishing a sovereign wealth fund.

3.1 Geographical Concentration of Reserves

The geographic resource concentration, measured by the Herfindahl-Hirschman Index (HHI) (calculated as the sum of the squares of individual countries’ shares of global reserves), for nine of the metals covered in this chapter is higher than for crude oil (see Table 3.2). The only metals with lower concentration than oil are copper and tellurium. The PGEs have the highest concentration (HHI = 8373 of maximum 10 000) followed by lithium (HHI = 3893), vanadium (HHI = 3298) and cobalt (HHI = 2832). As a reference point, the United States Department of Justice considers HHI value between 1500 and 2500 to be moderately concentrated and above 2500 as highly concentrated (US DoJ, 2010).

Six countries (Australia, Chile, DR Congo, China, Brazil and Russia) together hold the majority of reserves of cobalt (70 per cent), lithium (83 per cent), rare earths (65 per cent) and vanadium (83 per cent). This group of countries also holds a large share of copper (39 per cent), nickel (42 per cent) and silver (31 per cent) reserves. DR Congo, Chile, South Africa and China hold close to half or more of the global reserves of four metals (cobalt, lithium, PGE and

vanadium). These countries are thus important for future supply of these resources. Mining policies, fiscal incentives, taxes and environmental regulation in just a handful of countries can thus affect global supply and market prices. Collusion among these producers is possible but it is far from certain that it would be beneficial for the producers in the long term, as substitution (metal-by-metal or using other technologies), recycling and reduced metal intensity enable primary metal demand to respond to higher prices. These options provide a different dynamic for metal markets than has been the case for oil that is combusted when used.

In addition to holding reserves and extracting them, China is also a major actor in refining mineral concentrates into metal grades of the purity used in renewable energy technologies. For example, China is home to more than half the global refining capacity for lithium, cobalt and rare earths and has between 30 and 45 per cent of the capacity to refine copper and nickel. China also dominates manufacturing of key components used in renewable energy technologies (e.g., PM) and final products (e.g., solar PV). Other countries' dependency on China for these downstream stages of supply chains is therefore higher than indicated by proxies of resource concentration (Smith Stegen, 2015). However, supply networks are dynamic over time and can, unlike natural resources, change without redrawing state borders. Long-term assessments of supply and criticality therefore tend to focus on where reserves are located geographically rather than the concentration of refining and manufacturing capabilities.

3.2 Resource Revenues

Månberger and Johansson (2019) analysed how demand for 14 elements (metals and metal-loids) could increase as a result of a renewable energy transition and the size of the revenue that this could generate for countries holding reserves of these metals (Table 3.3). The study assumed that countries would extract a share of the global output proportional to their share of the reserve size reported by USGS (2018). Metal prices were assumed to trade in a price spread similar to the previous ten years. A sample of 37 countries was analysed, but the study only identified four countries that had the potential to generate revenues corresponding to more than 5 per cent of their current GDP (Chile, Cuba, DR Congo and Zambia).

An alternative baseline is to compare the economic value of extracted metals with countries' export revenues instead of their GDP. This comparison is better at capturing the magnitude required for mining to provide 'hard currency' for countries that have limited exports compared to the size of their present economies. From the same sample of 37 countries, ten countries (DR Congo, Cuba, Madagascar, Chile, Zambia, Indonesia, Australia, South Africa, Guatemala and Argentina) generate export revenues above 5 per cent of their current exports. Seven of these countries (Argentina, Chile, Cuba, DR Congo, Indonesia, Madagascar and Zambia) generate export revenues of around 10 per cent or more.

Battery metals (lithium, cobalt and some nickel) explain most of the value for the countries with around 10 per cent or more additional export revenue. It is the combined future primary demand and price that result in high revenues. Prices of these metals, particularly lithium and cobalt, have historically been volatile, more so than oil. It is therefore possible that average revenues are much lower than at the peak. The past price volatility can in part be explained by the small market size, lack of transparency and future price curve, and strong demand increase in recent years due to sales of EVs taking off. It is therefore likely that the volatility will be lower in the future if these conditions change. Countries can in part mitigate the impact of fluctuating resource rents by having sovereign wealth funds. However, estimates of state stability

Table 3.2 *Geographical concentration of major reserves by reserve holder for 2019*

Resource(s)	HHI	Share of Global Reserves (%)	Other Countries (%)
Cobalt	2832	Australia (17)	Canada, Russia and the Philippines (4 each)
Copper	814	DR Congo (49)	Russia (7)
Lithium	3893	Chile (21)	China (7)
Manganese	1781	Chile (57)	Australia (13)
Nickel	1346	South Africa (30)	Gabon (9)
PGE	8373	Indonesia (24)	Cuba (6)
REE	2159	South Africa (91)	Russia (9)
Silver	1243	China (37)	United States (1)
Selenium	1418	Peru (20)	India (6)
Tellurium	727	China (26)	Russia (10)
Vanadium	3298	China (21)	China (8)
Oil	1119	China (47)	United States (10)
		Venezuela (19)	Sweden (2)
		Saudi Arabia (17)	Australia (10)
		Canada (11)	Brazil (1)
			Iraq (9)

Note: PGE = platinum group elements; REE = rare earth elements and includes neodymium and dysprosium reserves. HHI = Herfindahl-Hirschman Index and is calculated as the sum of the squares of individual countries' shares of global reserves. A high value corresponds to a high concentration with the maximum value of 10 000. Oil is provided as a point of reference.

Sources: Table adapted from Månberger and Johansson (2019) with updated data from USGS (2019).

Table 3.3 *Basic data for 18 countries: reserves used in renewable energy systems that the respective countries possess; peak revenues attributable to increased metal demand for renewable energy during an energy transition up to 2060 compared to their GDP and export revenues; and estimates of current state stability^a*

Nation	GDP/ Capita 2016 (US\$) ^b	Metal Reserves	Oil Revenue/ GDP 2016 (%) ^c	Peak Metal Revenue/GDP (%) ^d	Peak Metal Revenue/Export Revenue (%) ^e	Current State of Stability ^f
Argentina	12 499	Li	1.8	1.1	9.6	More stable
Australia	54 069	Cu, Co, Li, Nd, Dy, Ag, Ni, Si	0.44	2.0	7.3	Very sustainable
Brazil	8 649	Li, Nd, Dy, Mn, Ni, Si	2.32	0.58	4.6	Elevated warning
Canada	42 154	Cu, Co, Nd, Dy, Pt, Ni, Te, Se, Si	4.66	0.93	3.0	Very sustainable
Chile	13 794	Cu, Li, Ag	0.03	10.5	37	Very stable
China	7 993	Cu, Li, Nd, Dy, Ag, Mn, Ni, Te, Se, Si	0.57	0.17		Elevated warning
Cuba	7 815	Co, Ni	0.89	14.0	96.0	Warning
DR Congo	512	Cu, Co	9.9	44.0	124.0	Alert
Indonesia	3 570	Cu, Ni		2.9	14.0	Elevated warning
Madagascar	451	Co, Ni	0	13	36.0	High warning
Peru	6 049	Cu, Ag, Te, Se	1.1	1.2	4.8	Warning
The Philippines	2 951	Co, Ni	0.1	1.2	3.8	High warning
Russia	8 655	Co, Nd, Dy, Pt, Ag, Ni, Se, Si	14.0	0.61	2.3	Elevated warning
South Africa	5 274	Co, Nd, Dy, Pt, Mn, Ni, Si	0.1	1.5	5.0	Elevated warning
US	57 808	Cu, Co, Li, Nd, Dy, Pt, Ag, Mn, Ni, Te, Se, Si	1.1	0.02	0.1	Very stable
Vietnam	2 171	Nd, Dy	2.9	1.6	1.7	Warning
Zambia	1 270	Cu, Co	0	8.3	24.0	High warning
Zimbabwe	998	Li, Pt	0	0.50	2.5	Alert

Notes and sources:

a. Table adapted from Månberger and Johansson (2019) with updated data and new estimates.

b. United Nations (2018).

c. The average oil price in 2016 was the lowest in ten years (US\$44/barrel) and these values are therefore lower than usual.

d. Highest value identified up to 2060. Note that GDP for 2016 is used in all comparisons.

e. Highest value identified up to 2060. Calculated using data from Månberger and Johansson (2019) and World Bank (2019).

f. Fund for Peace (FFP) (2019). The fragility of the nations is categorized in 12 groups from most sustainable to very high alert. This can give an indication of current fragilities but its usefulness in long-term analyses can be questioned (see, for instance, a discussion in Johansson, 2010).

(see Table 3.3) indicate that it is far from certain that the identified mineral holders have the institutional capabilities to do so and exchange their mineral wealth for prosperity.

It should be noted that all estimates of revenues are compared with current GDP and exports. The share of GDP attributable to increased metal demand for renewable energy would be (much) lower if economies are assumed to grow (or higher if economies contract).

Månberger and Johansson (2019) also found that producer revenues will increase up to mid-2030, after which recycling rates affect primary demand, and if recycling increases sufficiently it can cause revenues to reach a plateau or even decline due to peak demand. Assuming a technological disruption, primary cobalt producers are exposed to this situation if cobalt intensity continues to decline rapidly, as demand for primary cobalt can decline by half during a period of less than ten years.

3.3 Subnational Impacts

Church and Crawford (2018) compared the geographical distribution of metal reserves used in renewable energy technologies with estimates of states' levels of fragility and corruption. By doing so, they identified three hotspot regions: South America, Sub-Saharan Africa and Southeast Asia. The authors caution that local grievances and violence have occurred in the past due to mining, and the risk of such tensions is assumed to increase in the hotspot regions if a renewable energy transition takes place.

Conflict resources – that is, when resource rents are used to fund intra-state conflicts – is mainly a concern in poor, weak states. Conflict resources must be accessible and 'lootable', and it is therefore primarily minerals that can be mined profitably via small-scale mining by artisanal miners that meet these criteria (Le Billon, 2012; Lujala, 2010). Many metals perceived as critical for renewable energy technologies are extracted in low concentrations and produced as by-products from large-scale mining or metal refining. The scale and complexity make these metals unlikely to be conflict resources. Artisanal and small-scale mining is an important source of income in the Global South with more than 150 million depending on it for their livelihoods, but the targeted minerals are usually not used primarily for energy technologies – for example, tantalum, tin, gold, tungsten, diamonds and gemstones (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development [IGF], 2018).

However, there are examples where local geological conditions differ so that critical energy metals can be profitably extracted at a small scale. A case in point is some of the cobalt deposits situated in DR Congo. Studies of Congolese cobalt mining have documented that on the one hand it provides opportunities for poverty reduction and local development, and on the other hand it can lead to violent conflicts and environmental pollution (Sovacool, 2019). The issue is complex, as the outcome is a result of policies from government (national and local), the mining sector, local communities and industries that purchase the cobalt. Sovacool (2019) cautions against outright banning of cobalt produced by artisanal miners as it provides a source of income in poor regions, and instead suggests a path forward with joint ventures and benefit-sharing agreements involving small- and large-scale miners and government agencies.

4 CONCLUSIONS

Low-carbon energy transitions are material intensive and use metals that are perceived as critical. Markets provide flexibility over longer periods of time and price signals can incentivize reduced metal use, substitution and increased recycling. The total amount of metals required for a global energy transition is therefore uncertain but likely to be lower than current reserve estimates for most metals studied here. Mining rates can be a supply bottleneck as it takes time to scale up mining and critical metals are often produced as by-products that are less responsive to price increases than host resources.

Reserves of critical metals used in renewable energy technologies are more geographically concentrated than oil. Previous studies have found that potential new mining revenues are generally low, but five countries have been identified that can obtain significant revenues when compared to the size of their current economies. This study identified a group of ten countries where metal export revenues could be higher than 5 per cent of current export revenues. Metals used in batteries explain most of this value and this observation is therefore sensitive to demand and prices for battery metals.

The local impact of mining for supplying metals used in low-carbon transitions has not been the focus of much research. Countries that hold reserves and are characterized by high corruption and fragile institutions are a cause for concern. The future is not pre-determined, but successful policy interventions are complex as they require several actors to be involved in the unlocking of prosperous development pathways for affected local mining communities and countries.

ACKNOWLEDGEMENT

This publication is a deliverable of MISTRA GEOPOLITICS, which is funded by the MISTRA – the Swedish Foundation for Strategic Environmental Research.

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