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The electric vehicle revolution: Critical material supply chains, trade and development

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Abstract

The emergence of a mass market for electric vehicles (EVs) offers development opportunities for countries that have abundant resources of cobalt, nickel, lithium, copper, aluminium and manganese. Not surprisingly, developing countries have proposed ambitious plans to expand production of these raw materials. However, an observation from the resource curse literature is that strong institutions are required if they are to mitigate the risk of poorly directed, often excessively procyclical, investment, not least because of the complexity, opacity and price volatility of many raw materials utilised by global EV value chains. This paper examines the outlook for EV demand and associated raw material usage paying attention to the drivers and sensitivities required to assess and track future market transformations. These end use shifts are then placed in the context of the broader supply chain adjustments and trends shaping the demand. For resource exporters, adapting to structural change will require fiscal, regulatory, environmental and institution reforms designed to capture shifting patterns of resource wealth in a way which takes appropriate account of comparative advantages in specific value chains and mitigates adverse environmental and social consequences from their extraction and processing.

KEYWORDS
critical materials, electric vehicle, global value chains, resource mobilisation

1 | INTRODUCTION

The Paris Agreement brought the issue of climate change to the fore of international politics, hailing massive structural changes in the energy sector. Passenger and road freight, which are overwhelming fuelled by oil products, account for around six giga-tonnes of carbon dioxide (CO_2) annually (IEA, 2019). The automotive sector is thus facing a fundamental regulatory challenge to deliver a step change in emissions intensity that will require massive investment to support the development of a mass market for electric vehicles (EVs) alongside rapid decarbonisation of the power industry.

The EV revolution has significant implications for mineral-abundant regions of the world, many of which are already highly reliant on the global automotive industry as a source of demand. In South Africa, for example the mining sector supplies a range of inputs, including manganese for alloying steel body sheets and precious metals (notably platinum, palladium and rhodium) for use in auto catalysts. These supply chains are potentially at risk from a shift towards lighter, more aluminium or carbon fibre-rich, chassis (required to maximise driving ranges) and the eradication of tail pipe emissions.

At the same time, the demands of the electric mobility sector are likely to drive demand for new raw materials. The World Bank (2017), for example concludes that 'the technologies assumed to populate the clean energy shift, – wind, solar, hydrogen, and electricity systems – are in fact significantly more material intensive in their composition than current traditional fossil-fuel-based energy supply'. Analysis by Jones et al. (2020), for example suggests that for EVs alone, demand in 2030 for cobalt, lithium, manganese and nickel is projected to increase by 39.6, 19.6, 5.2 and 4.7 times, consumption levels in 2015, respectively. The IEA (2021a,b) note, for example that a typical electric car requires six times more mineral inputs than a traditional car (excluding steel and aluminium).

Already these effects are being felt among (mostly developing world) resource exporters. Between 2009 and 2019, for example production of lithium in Argentina and Chile increased by around 290 and 240% (to 6.4 kt and 18 kt) respectively (USGS, 2010a, 2020a). Over the same period, cobalt production in the Democratic Republic of Congo (DRC) increased by 400% to around 100 kt annually (OECD statistics; USGS, 2010b, 2020b). Key materials used in the manufacture of EVs (notably lithium, cobalt, manganese, nickel, copper and graphite) exceeded 20% of total 2018 export values for the DRC, Chile, Armenia, Georgia, Peru and Mongolia.[1]

This contribution of this paper is to provide guidance for resource exporters on the scale, time-path and determinants of the EV market transformation and associated raw material demand. The purpose is to help policymakers mitigate the considerable challenges for supply chain and infrastructure development which result from deep structural uncertainty reflected in in the broad range of projections for future market development. The IEA (2020), for example forecast that global EV sales could reach 27 million by 2030 under their EV30@30 (rapid transformation) scenario, while Jones et al. (2020) simulate annual global EV sales of 15.7 million in 2030 under their base case scenario in 2030 (compared with around 2 million in 2021).

[1]In addition to cobalt and lithium, the use of rare earth elements is also essential for the manufacture of the permanent magnets used in EV motors including but not limited to neodymium, praseodymium, dysprosium and terbium.

Price volatility is a particularly deleterious symptom of rapid, yet highly uncertain, demand growth, coupled with supply frictions. While this issue is pervasive across commodity markets (Redlinger & Eggert, 2016), it is particularly acute in EV value chains: Lithium prices, for example have approximately quintupled in the 14 months from January 2021 until the time of writing following pandemic disruption to supply chains. More recently, the price of nickel, which used to be a cheaper substitute for costly and price volatile cobalt, suddenly more than doubled following the outbreak of hostilities between the Ukraine and Russia. Moreover, the impact often weighs more heavily on developing countries where institutions and informational conditions are often weak and investor appetite most fragile.

As such, this paper draws on simulation results from the CoMIT model, introduced by Jones et al. (2020), to analyse the EV global value chain from a primarily developing country perspective, accounting for projections of future EV demand, the associated raw material usage and the key drivers and sensitivities that are required to track future market transformation. To complement existing analyses of the EV ramp up and associated mineral demand (Jones et al., 2020; World Bank, 2020), we also place these demand shifts in the broader context of the supply chain adjustments and trends which critically shape the enabling environment and associated policy needs. More specifically our contribution is to assess the key fiscal, regulatory and institutional reform priorities as well as the existing market barriers that may prevent successful domestic EV related resource mobilisation in developing countries.

We build on the theoretical literature relating to both global supply chains and the resource curse. Lessons from the former suggest that for many developing countries, which may have already been experiencing slow growth or premature industrialisation (Rodrik, 2016), exporting via global value chains offers a solution to weak industrialisation (Taglioni & Winkler, 2016). Improved information and communications mean that it should be easier than ever for developing countries with endowments of raw materials to access global markets (Baldwin, 2016) and that participation in global value chains can improve productivity through specialisation, knowledge spillovers and pro-competitive effects (Criscuolo & Timmis, 2017). For example, Coe and Yeung (2015) argue that Asian countries have benefited greatly from engaging with global value chains driven in part by the development of a sophisticated regional supply network.[2]

However, mineral endowments are also associated with the so-called resource curse whereby mineral-dependent countries underperform economically, first described in the literature by Gelb et al. (1988) and Auty (1993) (reviewed by Frankel, 2010 and Ross, 2014). At the core of the debate is whether the extraction of exhaustible natural resources impedes development by placing upward pressures on exchange rates, restricting innovation in the broader economy, encouraging political, social and institutional instability (Gilerthorpe & Papyrakis, 2015), or by fostering inefficient and volatile spending and borrowing (resulting in periodic credit market dislocation).

Hence, efforts to promote transparency around the scale and nature of the opportunities and risks to the mining industry from major structural shifts in global demand. Enabling policymakers to adapt to these demand changes is key to developing institutional capacity as part of efforts to support long-term value creation. In so doing, this may help countries avoid some of the pitfalls associated with myopic

[2]Costinot et al. (2013) provide an elemental theory of global supply chains to explain how today's production processes involve, what Hummels et al. (2001) call, vertical specialisation and how technological progress can affect different countries operating in the same supply chain. More recently, Antras and de Gortari (2020) develop a multi-stage general equilibrium model of GVCs with international trade barriers to show that location matters (as well as marginal costs) when deciding the optimal location for a given stage of a GVC. Other relevant theoretical contributions to the supply chain literature include Antras and Chor (2013) and Fally and Hillbery (2018).

and irrational behaviour which are often at the core of the resource curse (Mehlum et al., 2006a,b).[3] These issues may be particularly acute given the relatively small scale (and thus volatile) and opaque nature of some EV-related raw materials markets at this stage of the EV development cycle.[4]

Empirically, there is a small but growing literature that examines the role of critical materials in global supply chains. For example, Eggert et al. (2016) discuss the how rare earths can disrupt markets and global supply chains from exploration, through to separation, end use and recycling, while Olivetti et al. (2017) look at different bottlenecks that may lead to shortages in cobalt and lithium. Finally, Habib et al. (2016) provide a dynamic perspective on the geopolitical supply risk of metals more generally while Tisserant and Pauliuk (2016) show how cobalt demand is impacted under different co-production and mining attractiveness assumptions.

In the context of the raw materials critical to the EV revolution, a key element is whether the demand for such materials provides an opportunity for developing countries to not only expand their exports of primary ores but also to move up the value chain and develop a domestic primary ore processing sector. Such a process of vertical integration may allow countries (and domestic firms) to develop modern management techniques, improve product quality and become globally competitive. In this paper, we disentangle these impacts and discuss the broader policy implications.

The analytical framework that we present in this paper allows us to make the following observations. First, growth in EV demand offers potential development opportunities particularly for countries which have well-aligned resource endowments, strong institutions and sound enabling conditions. From a fiscal standpoint, expanded domestic resource mobilisation has the potential to boost public revenues. However, to really benefit, countries may require institutional and informational reform to address the administrative challenges that may arise from the fundamental complexity and opacity of the GVCs, and current trends towards more vertical integration between suppliers and end-users (as well as increased buying power, particularly among certain Asian governments and corporates).

Second, from a sector perspective, it is important that economic forecasts can account for the policy, economic, consumer and technological drivers and associated risks surrounding future EV raw materials demand (including the potential for extreme price volatility and competition from alternative suppliers). As with other natural resource industries, knowledge gaps on the existence and nature of geological deposits are likely to be a key barrier to enhanced resource mobilisation in many developing countries. This is likely to justify greater emphasis on geological research in ore bodies that may host EV raw materials.

Finally, the concentration of value within the mid and downstream segments of critical EV raw material chains, such as lithium and other battery cathode inputs, raises often vexed questions regarding the strategic case for expanding domestic processing and refining capacity. While seemingly politically attractive, moving down the value chain may be challenging for many developing countries, particularly in Africa and Latin America, where local demand, technological know-how and the availability of other factors of production (including a workforce with the necessary specialist skills and sufficient, competitively priced power) are often lacking. Such a transition also risks increasing the environmental and social externalities associated with EV raw material production and processing. Addressing these issues requires effective implementation of complementary fiscal and regulatory

[3]Limiting the 'appropriability' of natural resource rents through both technical and institutional channels has been identified as key mechanisms for mitigating economic risks from natural resource extraction (Boschini et al., 2007).

[4]Cobalt, lithium and rare earth prices are particularly volatile because demand can easily be overwhelmed by supply responses where supply can be impacted by unrelated mineral market conditions and exchange traded pricing is absent or is still in its infancy.

reforms (which may also become increasingly critical for market access, given changing customer and other stakeholder preferences for higher production and environmental standards).

The remainder of the paper is organised as follows. Section 2 examines how the EV sector may impact future raw material demand, drawing on comparative static results from the CoMIT model. Section 3 places the results of these end use and associated raw material demand shifts within the broader context of the international supply chain trends and adjustments which are required to enable this market transformation. Section 4 discusses the implications for raw material exporters in terms of revenues, tax administration and value creation as well as outlining the principal environmental and social risks and associated with the mining and exporting these raw materials. Section 5 concludes.

2 | ELECTRIC VEHICLES AND RELATED RAW MATERIALS DEMAND

2.1 | EV market evolution to date

Despite a decrease in new car registrations in 2020 due to the COVID-19 pandemic, global electric car sales continued the rapid growth which has been observed over the past decade. Approximately, 2.7 million new EVs (including full battery and plug in hybrid variants) were registered globally. Figure 1 shows the increase in demand for the two types of electric vehicle for the main EV markets. Notably, Europe overtook China as the largest adopting region (with 1.4 and 1.2 million EVs registered, respectively). The United States ranked third with 295,000 new electric cars. Overall, the global stock of EV surpassed 10 million, with China still host to the largest electric car fleet of 4.5 million.

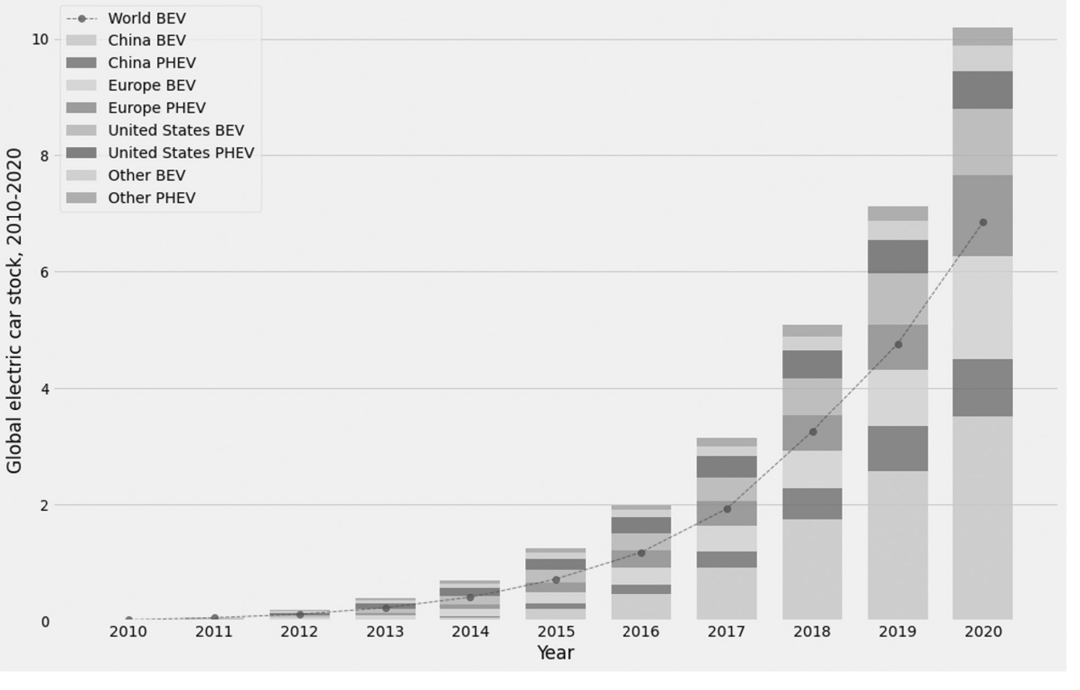


FIGURE 1 Global EV stock 2010–2020 (millions).
Source: IEA (2021a, 2021b). BEV, Battery electric vehicle; PHEV, plug-in hybrid electric vehicles

2.2 | Demand outlook and key sources of uncertainty

Looking to the longer term, many forecasters are generally bullish regarding the future of e-mobility. Figure 2 presents the estimates from three different reports. IEA (2020), for example, project cumulative global sales of plug in and full battery EVs of around 120 million by 2030 under the Stated Policies Scenario. However, this number increases to around 200 million by the same period in the Sustainable Development Scenario. Jones et al. (2020) project EV sales to be around 15.3 million in their base case by 2030 (and 114.4 million cumulatively over the period 2015–2030).

Given the complexity of the systemic changes and the dependency on future public policies, uncertainty regarding the scale and timing of energy sector transformations is to be expected. This commonly leads to large error bounds in medium and long-term forecasts of EV adoption.[5] This is a particularly significant issue in the context of EV adoption because the volume and mix of mineral inputs differs even within technologies. For example, Figure 3 presents the lithium requirements according to the different vintages of lithium-ion battery (LiB) technology.[6]

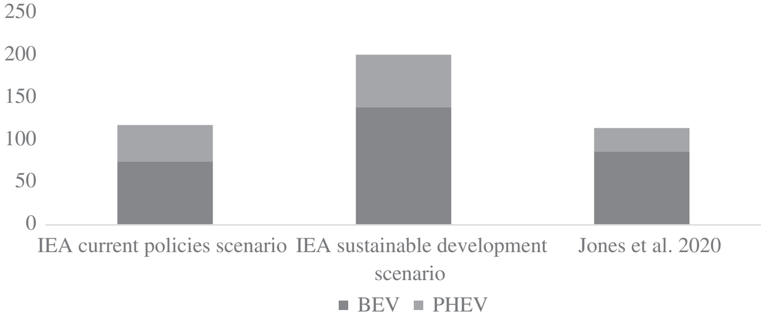


FIGURE 2 Cumulative EV sales by 2030 by scenario/study (millions).
Source: Author's calculations based on IEA (2020), Jones et al. (2020)

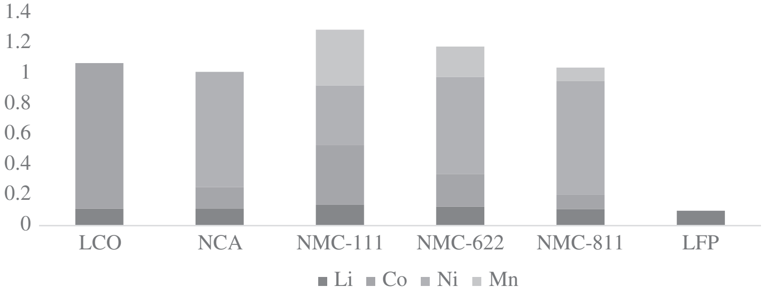


FIGURE 3 Elemental requirements by LiB cathode technology, kg/kWh.
Source: Author's calculations based on Olivetti et al. (2017) and Xu et al. (2020)

[5]For example, in the case of forecasting future renewables diffusion, the IEA's, 2017 estimate for capacity growth to 2022 was one-third higher than its 2016 estimate (IEA, 2017).

[6]These include lithium-nickel-manganese-cobalt oxide (or NMC) batteries which are widely used in electric vehicle models such as the Chevrolet Bolt, the BMW i3 and the VW e-Golf (of which there are different sub-types featuring different ratios of nickel and cobalt). In addition, lithium-nickel-cobalt-aluminium oxide (or NCA) batteries are used in numerous best-selling EVs in the United States (such as the Tesla Model S).

The IEA (2019) show, for example that demand for lithium and cobalt is approximately 170–190 kt higher in 2030 in their 2 Degree Scenario relative to the Stated Policies Scenario. However, these ranges become broader still, potentially nearly doubling in scale, when uncertainty regarding the future mix of battery of technologies is factored in (IEA, 2020). To put a rough sense of scale on to these uncertainty bounds, the differences between these future scenarios, even leaving aside those associated with heterogenous mineral utilisation within LiB technologies, are significantly greater than the entire global market for these commodities today.

Such deep structural uncertainties, while to a certain degree unavoidable, nevertheless create substantial problems for both investors and policymakers. For policymakers, it involves imparting considerable uncertainty into revenue forecasting and increases the risk of inefficient and mistimed investment. Hence, for effective strategic policy planning a robust and regularly updated view on mineral demand from EVs is necessary.

2.3 | Assessing demand: A comparative static approach

Given the set of previously discussed demand-related issues, we characterise some of the key factors that are shaping EV adoption and associated raw material demand. The CoMIT model, originally developed by Jones et al. (2020), provides a robust framework for evaluating the scale and timing of the market transformation, together with the relevant Cost (Co), Macro (M), Infrastructure (I) and Technology (T) related drivers, and their associated impact on metal demand (the model also has the attractive feature of being transparent and simple to update when new data becomes available).

Our analysis examines the sensitivity of mineral demand to changes in four factors, namely, (1) the rates of global economic growth; (2) technological advances in the battery sector; (3) levels of policy support (with a focus on China) and (4) drivers of consumer behaviour (in particular, EV prices and the discount rate over which future operating cost savings are amortised). These drivers, together with a summary of the specific simulations undertaken, are outlined in Table 1, while the quantitative impacts and sensitivity analysis is summarised in Figure 4.

We assess the impact of each driver against demand for six different critical materials, cobalt (CO), lithium (Li), manganese (Mn), nickel (Ni), copper (Cu) and aluminium (Al). We choose to present the results for high and low estimates that are based on a 50% increase or decrease in the variable(s) concerned. The key sensitivities that influence EV-related raw materials demand are found to be (1) the evolution of battery cell and broader EV manufacturing costs and (2) the extent and pace of market penetration in China.[7] For (1) a doubling of the decline rate in EV capital cost would result in an explosion in the demand for materials such as cobalt and lithium whose demand is shown to be approximately 285 and 225 kt higher in 2030 compared with the base case, respectively. For (2), a 50% uptick in Chinese consumer demand places the global supply of cobalt and lithium under significant additional pressure, with incremental demand of the order of 70 kt and 45 kt higher in 2030, respectively.

[7]Aluminium is an exception with material choices over the automotive body sheet in particular being the most important individual driver of demand growth.

TABLE 1 Overview of EV-related mineral demand drivers and comparative static analyses

Driver	Key variables	Simulation notes
Upfront payments (Consumer choice)	EV price deflation Fuel costs	50% increase and decrease in the rate of change EV/battery capital costs
China electrification (Policy support)	EV subsidies Fleet standards Tail pipe standards	50% increase/decrease in EV penetration in China due to policy adjustments
Economic Growth (Macroeconomics)	Real GDP growth	50% increase and decrease in the baseline rates of economic growth
Technological Progress	Battery size Battery mineral intensity Vehicle weight Recycling	50% increase and decrease in the rate of change in metal loadings associated with LIBs and aluminium utilisation in EVs 50% increase and decrease in battery size/driving range
Discount rate	Interest rate	50% increase and decrease in discount rate
Recycling	Volume of recovered secondary materials	Not simulated

Source: Authors.

3 | ELECTRIC VEHICLES AND THE RAW MATERIAL SUPPLY CHAIN

3.1 | The importance of a supply chain perspective

Research on EVs has tended to focus on demand-side issues that impede the decision of consumers to purchase an EV, for example the lack of charging infrastructure (see e.g. Hagman et al., 2016; Lévay et al., 2017). However, with automotive industry players announcing considerable EV-related investment (Volkswagen alone have committed to spending over 33 billion Euros in developing electrified powertrains between 2019 and 2023), a range of potential technical and investment challenges have the potential to emerge at different stages of these complex and multi-staged supply chains. These could extend, not only to ensuring adequate production of primary ores but also the manufacture of intermediate and semi processed products and new patterns of economic value creation. For example, the safety, durability and charging performance of an EVs battery. The change in preference is in part determined by the quality of the chemical and mineral feedstocks and is likely to be a key product differentiator (compared to say the quality and price of the engine and transmission systems in traditional vehicle markets).

Understanding supply chains requires a good understanding of the market structure, dynamics and locus of economic value. By way of introduction, Figure 5 (upper panel) presents a high-level schematic for the LiB supply chain, including raw material extraction and processing, cell component manufacture and final battery assembly. The lower panel provides a more detailed illustration of material flows for the case of cobalt, in which primary extraction and, increasingly, intermediate refining, is concentrated in the DRC. However, refining and chemical synthesis occurs largely in China,

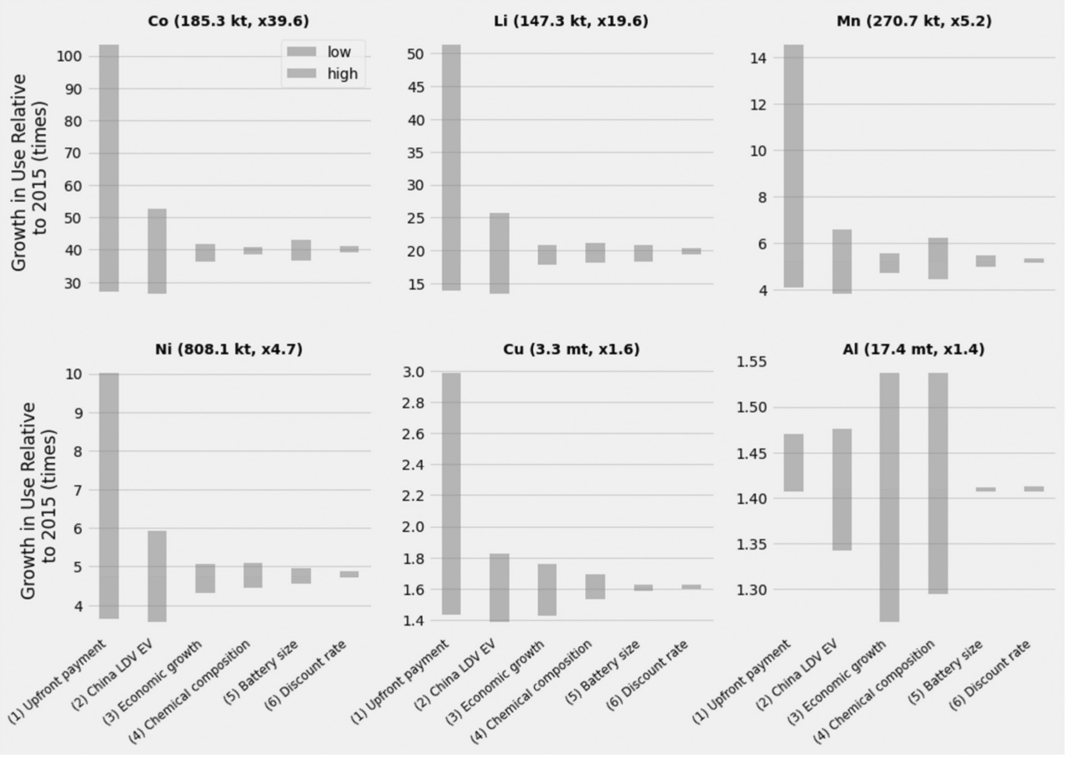


FIGURE 4 Summary of change in mineral demand in 2030, by demand driver.
Source: Author's own calculations based on CoMIT model (Jones et al., 2020). Cobalt (CO), lithium (Li), manganese (Mn), nickel (Ni), copper (Cu) and aluminium (Al). The y-axis indicates mineral demand for EVs in 2015 (times). The x-axis indicates factors that may drive EV sales and are adjusted by high and low scenarios, which correspond to the red and blue bars, respectively. The title of each graph indicates mineral name abbreviations and their projected demand in 2030 under the baseline scenario (in parentheses). The projected demand is expressed in absolute values, followed by relative values (comparison with estimated demand in 2015).

with component manufacturing and cell assembly predominantly in China and elsewhere in Asia.[8] A number of key issues that impact the development of each supply chain segment are discussed in turn.

3.2 | EV primary raw material supply trend

From the perspective of primary raw materials markets, for example the diffusion of EVs (and broader related trends including the growth of grid storage to support deeper penetration of renewable power) is already starting to have a transformative impact, particularly on markets for ores which are small in scale and highly exposed to these end uses (Jones et al., 2020). Figure 6 shows the major (predominantly developing) countries that mine raw materials essential for EVs manufacture (such as cobalt, graphite, lithium, manganese and nickel). In 2020, the DRC supplied nearly 70% of the global

[8]Individual minerals may be subject to numerous processing steps before being manufactured into a battery component. For example, nickel sulphate, the key nickel bearing chemical used in precursor manufacture, can be produced in more than a dozen different ways, each subject to different economics and technical valuations.

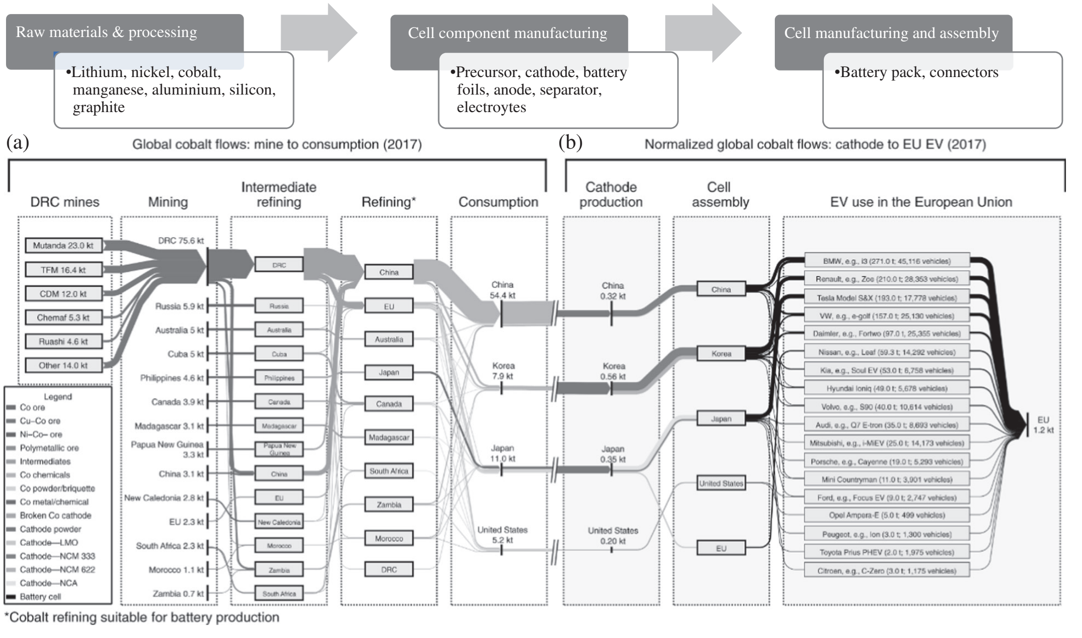


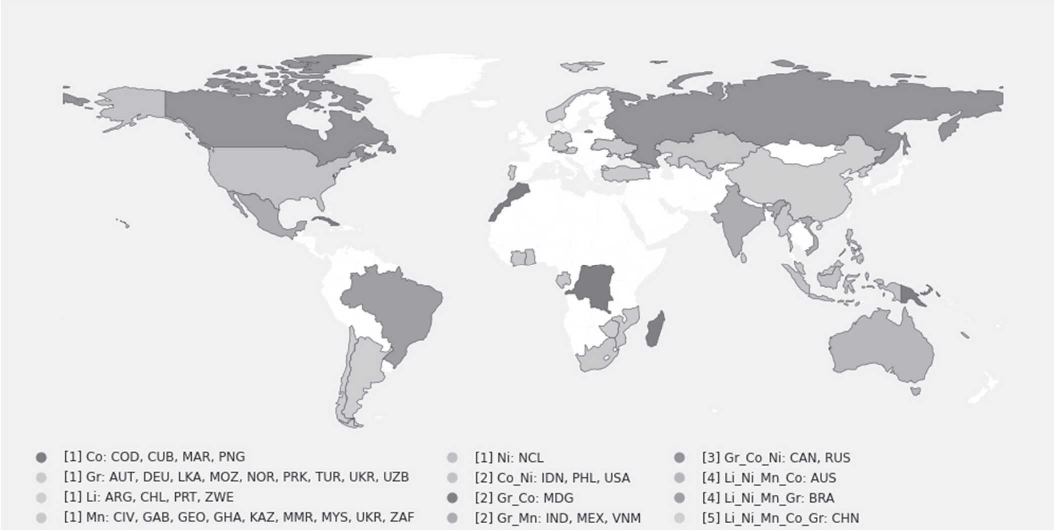
FIGURE 5 LiB supply chain and raw material inputs (upper panel) and specific supply chain of cobalt (Baars et al., 2021) (lower panel).
Source: Baars et al. (2021) and authors

cobalt production, and emerging countries such as China and Brazil produce a range of commodities vital for EVs.

In the case of lithium and cobalt, batteries for EVs account for approximately 40–50% of overall market demand. For other markets such as nickel or manganese, which have more diversified applications (being predominantly used for production of steel alloys), the current share is considerably smaller (often below 5%). However, the growth outlook is buoyant, meaning that these end uses are set to become increasingly important market drivers. Jones et al. (2020) project that EVs and associated charging infrastructure build out will account for around a quarter and one-sixth of total demand growth in aluminium and copper; and a nearly 5-fold increase in nickel utilisation in EV's by 2030, (equivalent to around 20–25% of current consumption). Hence, EV diffusion has the potential to be a key driver of investment across a broad spectrum of commodities, not just lithium and cobalt that tend to get the headlines in the popular media.

The trends in demand for critical materials for EVs, if they continue, are set to have a major bearing on raw material trade flows with the concomitant supply chain risks. This is largely a result of the geographical mismatch between auto-chain production growth (centred in Asia, Europe and, albeit to a lesser extent, the United States) and the locus of resource production (dominated by Australia, the Americas and Africa). Jones et al. (2020) find, for example that China's share of global lithium and cobalt demand for transport (increasingly the dominant end user) is likely to rise to about 68% by 2030.

Figure 7 presents the share of export revenues by EV-related commodity for 2020 and shows which countries are the most dependent on critical materials. From Figure 7, we can see that Namibia and DRC are the main exporters of cobalt while Zimbabwe and the Philippians have nickel as an important export. The main observation is the importance of copper for many developing countries with shares over 20% in six different countries.



Material (abbr.) [2020 Global Production]	Top miners (ISO3 Country codes) [2020 Global Share]
Cobalt (Co) [142kt]	Democratic Republic of the Congo (COD) [69.01%]; Russia (RUS) [6.34%]; Australia (AUS) [3.96%]; Philippines (PHL) [3.17%]; Cuba (CUB) [2.68%]; Canada (CAN) [2.6%]; Papua New Guinea (PNG) [2.07%]; Morocco (MAR) [1.62%]; China (CHN) [1.55%]; Indonesia (IDN) [0.77%]; Madagascar (MDG) [0.6%]; United States of America (USA) [0.42%]
Graphite (Gr) [966kt]	China (CHN) [78.88%]; Brazil (BRA) [6.58%]; Mozambique (MOZ) [2.9%]; Russia (RUS) [2.59%]; Madagascar (MDG) [2.16%]; Ukraine (UKR) [1.66%]; Norway (NOR) [1.24%]; North Korea (PRK) [0.84%]; Canada (CAN) [0.83%]; India (IND) [0.62%]; Vietnam (VNM) [0.52%]; Sri Lanka (LKA) [0.41%]; Mexico (MEX) [0.34%]; Turkey (TUR) [0.26%]; Austria (AUT) [0.05%]; Germany (DEU) [0.03%]; Uzbekistan (UZB) [0.01%]
Lithium (Li) [82kt]	Australia (AUS) [48.12%]; Chile (CHL) [26.06%]; China (CHN) [16.12%]; Argentina (ARG) [7.15%]; Brazil (BRA) [1.72%]; Zimbabwe (ZWE) [0.51%]; Portugal (PRT) [0.42%]
Manganese (Mn) [19Mt]	South Africa (ZAF) [34.39%]; Australia (AUS) [17.62%]; Gabon (GAB) [17.51%]; China (CHN) [7.09%]; Ghana (GHA) [3.37%]; India (IND) [3.34%]; Ukraine (UKR) [3.06%]; Ivory Coast (CIV) [2.78%]; Brazil (BRA) [2.61%]; Malaysia (MYS) [1.84%]; Myanmar (MMR) [1.34%]; Mexico (MEX) [1.05%]; Georgia (GEO) [0.98%]; Kazakhstan (KAZ) [0.84%]; Vietnam (VNM) [0.64%]
Nickel (Ni) [3Mt]	Indonesia (IDN) [30.72%]; Philippines (PHL) [13.31%]; Russia (RUS) [11.27%]; New Caledonia (NCL) [7.97%]; Australia (AUS) [6.73%]; Canada (CAN) [6.65%]; China (CHN) [4.78%]; Brazil (BRA) [3.07%]; United States of America (USA) [0.67%]

FIGURE 6 EV primary raw material supply by country (percentage of global total in 2020).
Note: The map legend shows the list of top miners by the (combination of) key EV raw materials (cobalt, graphite, lithium, manganese and nickel). Numbers in square brackets are number of commodities mined (e.g. [5] for China, which produces Li, Co, Mn, Ni and Gr).
Source: USGS (2022)

3.3 | Battery market transformation

EV supply chains, particularly in cell and componentry segments, have become highly concentrated in a relatively small number of countries (in contrast to the regionalised nature of traditional automotive clusters). Figure 8 presents the current LiB cell capacity for a range of countries for 2020 and

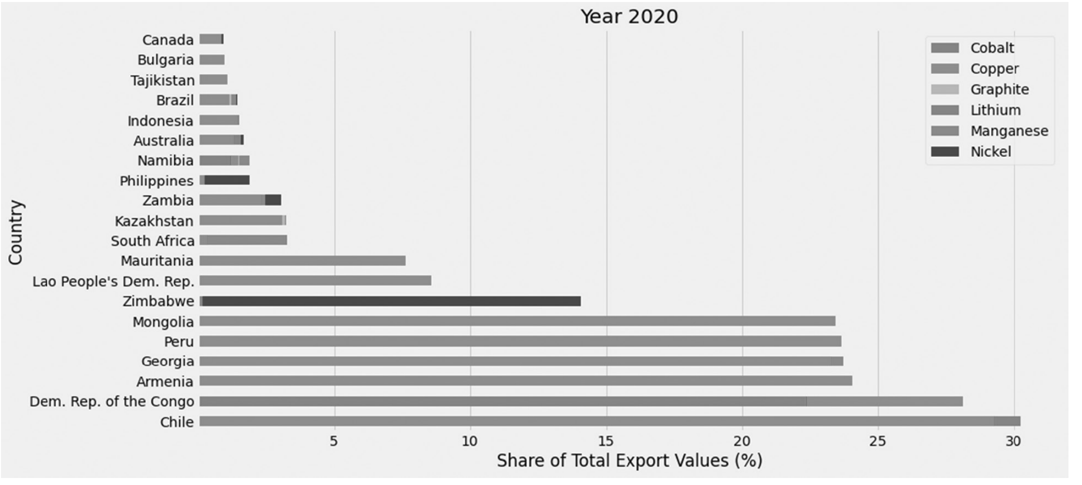


FIGURE 7 Share of export revenues by EV-related commodity in 2020.
Note: Figure illustrates the top 20 countries by the exports values of unrefined commodities related to six materials required for EVs, as a proportion of total exports. The data are from UNCOMTRADE using the following HS codes: l 253,090, 282,520, 283,691 for lithium; 260,500, 282, 200 for cobalt; 260,400 for nickel; 260,200, 2820 for manganese; 250,410 and 271,312 for graphite; and 260,300 for copper. These materials are important for different parts of EV batteries: cathodes (lithium, nickel and manganese), anodes (graphite) and collectors (copper). Note that these HS codes were not designed to isolate the use of these materials in EV manufacturing from other purposes and other compounds (oxides, hydroxides, carbonates, etc.) although they do constitute the major use of these commodities

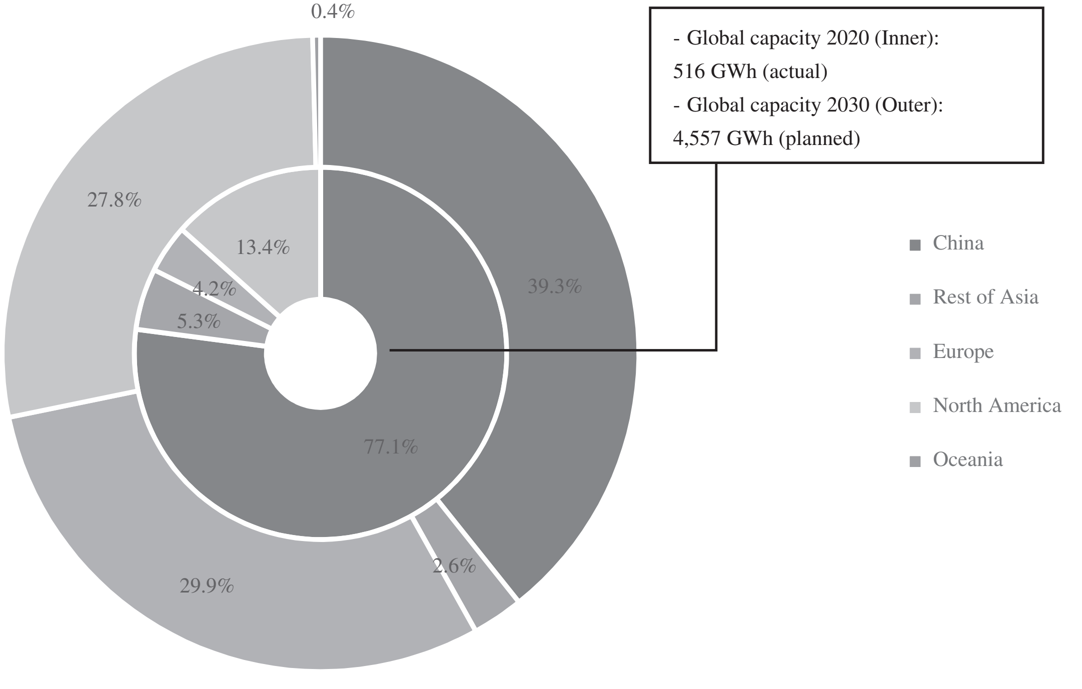


FIGURE 8 LiB cell capacity by region, 2020 (actual) and 2030 (planned).
*Source***:** CRU (as of August 2022)

shows China's dominance. While substantial investment in downstream cell manufacture is planned more broadly across regions, notably in Europe and North America, the pace of market expansion, the extent of China's existing market share and the strength of its own investment pipeline, mean that China is expected to account for around two-thirds of the global cell manufacturing market in 2030.

This market concentration by Asian producers is also observed elsewhere in the value chain, particularly in cell, component and intermediates manufacturing. In 2016, for example four countries, China, the United States, Japan and South Korea, hosted 97% of the total LiB manufacturing capacity (Mayyas et al., 2019). Japan and China combined, accounted for between two-thirds and four-fifths of major component markets, including cathodes, anodes, separators and electrolytes (Lebedeva et al., 2017) as illustrated in Figure 9. In some cases, market concentrations are increasing. For example, in the case of precursors and cathode active materials, between 2016 and 2022, China has been responsible for an estimated two-thirds of global capacity growth.

Moving further up the value chain, mineral processing capacity is also heavily concentrated in Asia. For example, China accounts for 47% of lithium carbonate and cobalt refinery capacity although there has been some rebalancing of processing capacity towards raw material exporters such as Australia in recent years (NREL, 2019). China also exerts significant dominance in other key intermediates markets such as manganese and nickel sulphate, as well as in rare earth mining and processing (a key input into magnets used in electric motors).

3.4 | Emerging trends in supply chain risk management

Enabling the energy transformation has focussed the minds of consumers, producers, investors and policymakers alike, particularly in the aftermath of the COVID-19 pandemic and the Ukraine crisis which saw increased trade frictions and the impact of sanctions heavily impacting GVCs. Many industrial buyers, anticipating elevated risks from supply chain bottlenecks or price spikes, have attempted to build supply chain resilience (and take advantage of some of the commercial benefits of securing stable raw material supplies, including through the ability to co-optimise downstream plants capacity to specific input specifications).

The need to secure supply chains has manifested itself in a shift towards negotiation of long-term contracts with producers (so-called offtake agreements). This trend stands in marked contrast to other more traditional commodity markets such as natural gas and iron ore which have gradually

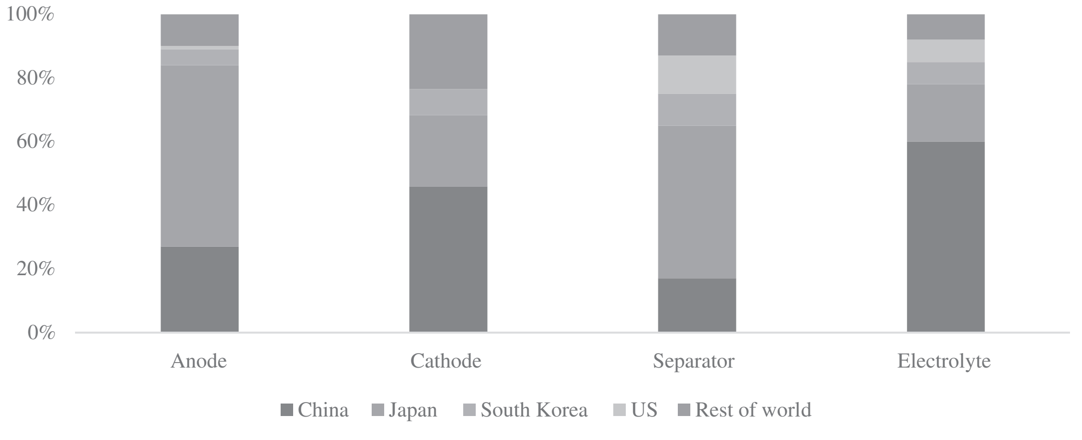


FIGURE 9 LiB component manufacturing capacity by region, 2015.
Source: Lebedeva et al. (2017)

moved towards exchange spot and futures trading. For example, in February 2020, Samsung signed a five-year deal with Glenore for the supply of cobalt hydroxide. Others have actively pursued vertical integration opportunities. For example, in 2019 a branch of Toyota acquired a 15% stake in Australian-based miner Orocobre to secure supply rights and help fund expansion of a lithium brine project in Argentina. Such strategic partnerships are increasingly observed across a broad suite of commodities. Tesla, for example, recently entered a long-term agreement for nickel with BHP from its Nickel West operation in Australia. An example of cooperation in the value segment space is the emerging battery cluster in the UK established around a tie up between new entrant investors in cell manufacturing (Britishvolt) and a downstream recycling plant (Glencore).

Governments in importing regions, such as the United States and EU, are also playing an increasingly strategic role including defining many battery materials as strategically critical.[9] Such a designation is spurring a range of policy responses, including directing trade finance towards investment in expanding EV value chains and broader regulatory measures designed to promote a more 'circular economy' (which places greater emphasis on recycling and reuse as a means of reducing raw materials import dependency). A number of advanced countries are also actively promoting the development of domestic battery manufacturing capacity. In 2019, for example, the European Commission warned 'the EU's high dependency on battery cell imports could expose the industry to higher costs and that risks to the supply chain could undermine the automotive industry's ability to compete with foreign competitors' (EU Commission, 2019).

While policies to support the mitigation of these risks have been somewhat slow to emerge, regional investment into the sector is now beginning to flow. For example, the European Investment Bank recently announced its intention to increase funding to battery-related projects to over €1 billion (US$ 1.1 billion) during 2020 alone (European Investment Bank, 2020). The US government has also started to intervene, including by funding domestic production of rare earth elements (which are a key input to EVs, wind turbines and the defence industry), in an effort to limit its import dependency on China (although it is currently required to ship the mined ores to China for processing). However, there is a relative dearth of analysis, to date, into the implications of these trends for developing country raw material exporters.

4 | IMPLICATIONS FOR RAW MATERIALS EXPORTERS

4.1 | Towards enhanced domestic resource mobilisation

Given the dramatic predictions of future EV demand, it is perhaps not surprising that over the last 10 years some developing country exporters have staked major claims on battery-related resource mobilisation. In some cases, however, these plans, and the associated (often publicly supported) investment plans, have taken insufficient account of the potential risks and challenges associated with market entry and/or expansion. The Bolivian government, for example, reportedly earmarked up

[9]The EU established a critical raw material list in 2014. In 2020, this list was revised to include lithium. The United States established a similar list of 35 minerals in 2018 which includes many EV inputs including cobalt, lithium, manganese and bauxite. In the new 2021 draft (USGS, 2021), the list was extended to 50 mined commodities and includes nickel. The US Department of Energy (2020) discusses how the United States is building a strategy to reduce its reliance of critical materials through partnerships with allies and partners, improving recycling and reprocessing technologies, better geophysical mapping of the United States and developing a stronger domestic processing facility. Critical materials also feature in the August 2021 US infrastructure bill (Reuters, 2021).

to one billion US dollars for public investment in the development of a domestic lithium industry.[10] However, implementation has been substantially impeded by a range of practical barriers, including prevailing, legislative, technical and enabling conditions.

Resource exporting governments in both developing and advanced countries are also beginning to adapt their policies to take fuller advantage of potential opportunities. In 2019, for example, Western Australia established a Future Battery Industry Strategy designed to promote more domestic downstream integration in these value chains (the state has been host to a substantial growth in lithium refining capacity in recent years) (Government of Western Australia, 2019). This is a notable departure from the previous focus of the region's mining industry that was based on shipping largely unprocessed ores.

At the other end of the development spectrum, the DRC classified cobalt as a strategic mineral and subjected it to a 6.5% additional royalty charge. This reform process was somewhat chaotic in nature and may have further fuelled investor concerns regarding the stability of the fiscal regime and broader sector governance in the country. However, the underlying economic case for an oligopolist, such as the DRC, wanting a significantly higher share of economic rent is perhaps worthy of fuller analysis (considering both the long-term price elasticity of demand for cobalt as well as the likely investor responses to reduced sector profits).[11]

On the face of it, many developing countries look set to benefit from increased raw materials needs. Latin America appears particularly well placed, for example given its large deposits of copper and lithium and recent advances in the deployment of renewable energies in its mining industries. Some countries in Southeast Asia and Oceania could also benefit, including those with nickel deposits such as Indonesia, Malaysia, New Caledonia and the Philippines. Naturally, Africa is also a highly mineral-rich region: for example, South Africa and Ghana produce manganese, Zimbabwe has lithium deposits, Madagascar is a major nickel producer, and the DRC and Zambia have significant copper and cobalt deposits. The magnitude of the economic impact depends on the size of the industry relative to the size of the overall economy. In the case of small and highly undiversified economies such as New Caledonia or Madagascar, the implications could be considerable.

However, the existence of known deposits is no guarantee of future domestic resource mobilisation. The market for investment in natural resources is highly competitive, and foreign direct investment flows are highly sensitive to domestic policy conditions and, interrelatedly, the quality, cost and risk associated with the specific resource development project being considered (as well as the quality of the policy and wider enabling environment). Thus, the growing economic and strategic priority being placed on raw materials for EVs (and other low-carbon technologies) increases the need for countries to understand how to 'debottleneck' the key constraints to domestic resource mobilisation. These concerns are particularly important in a developing country context.

[10]Mariette, Maëlle. 'In Bolivia, the Lithium Sector up for Auction'. Le Monde Diplomatique. January 2020. https://mondiplo.com/en-bolivia-el-sector-del-litio-a-subasta.

[11]Cobalt can be substituted for nickel in EV cathodes (cobalt content reduced and nickel content increased). Nickel is also cheaper per unit of performance in NMC cathodes and avoids reputation risk associated with child labour concerns in the DRC. These substitution effects currently appear to be moderate, and perhaps, declining (although this trend is partly influenced by shifting relative metal prices). However, demand responses could be non-linear particularly if new, chemically stable cobalt-free, battery cathodes are successfully developed. Supply and investment responses are themselves dependent on the cost competitiveness of domestic assets (higher taxation is passed through to mineral prices where reforms impact marginal suppliers, and, where margin reductions occur, these are typically less consequential for lower cost producers), the availability of alternative investable deposits internationally, as well as prevailing and expected market conditions (including for co-produced nickel and copper).

In many cases, bottleneck concerns are likely to sharpen the pre-existing case for policy reforms such as enhancing infrastructure provision and the introduction of transparent and predictable fiscal and regulatory measures including those designed to control pollution and mitigate wider external impacts from mining and mineral processing (Addison, 2018). However, such generic policy prescriptions also need careful interpretation and tailoring to take account of the specific economic, social and physical characteristics of the value chains and production process in question and the broader market context in which the transformation takes place. We now discuss several of the key issues in more detail.

4.2 | Exploration and geo-information policy

A lack of basic information regarding the existence and nature of geological deposits is a perennial barrier to domestic resource mobilisation, particularly (but by no means exclusively) on the continent of Africa. Many governments, supported by international and national geological agencies, have invested in improving the quality and accessibility of geological survey information (including the introduction of electronic cadastres and geological data hubs), developing and reforming legislation on sub soils use and private sector investment promotion. Growth in EV raw materials demand generally reinforces the case for such investments. However, it may warrant the prioritisation of geological research and early-stage prospecting into new ore bodies that may host battery materials.

Countries should also review the results of previous geological survey data and samples. Many For example, many lithium-bearing deposits remain undiscovered due to the fact that previous public or private prospectors tended to explore for tantalum, tin, caesium, potash or other potentially co-located minerals but did not test for the presence of lithium given the then absence of a viable market. There may also be a case for public intervention in such processes, perhaps in conjunction with the university sector or geological surveys, to encourage resampling of the results (or 'signatures') of historical pegmatite and other exploratory drilling in order to help catalyse investment in potentially newly commercially viable deposits.[12]

4.3 | Revenue and economic forecasting

A number of developing country exporters are pushing hard for domestic mobilisation of EV raw materials in an effort to increase exports and fiscal revenues. In 2017, for example, as previously touched on, the then President of Bolivia, Evo Morales, told a German news agency that 'We will develop a huge lithium industry, over $800 million have already been made available'.[13] Bolivia's move into lithium production included planned leadership by the Bolivian state-owned company Yacimientos de Litio Bolivianos in the development of 14 plants at the Salar de Uyuni project by the mid-2020s (targeting 50 kt of output within 5 years). Three years later, after disbanding a joint venture agreement (with German company, ACI Systems), in the face of numerous technical, economic and legislative barriers, the plan was effectively abandoned.

[12]There are numerous examples of such activities by private companies, for example, in Australia and Canada. However, these successes are fuelled by vibrant junior mining industries (which are commonly lacking in many developing countries, particularly those with nascent mining industries), which benefit from improved prospecting opportunities due to the availability of richer and more accessible geoinformation data and platforms.
[13]See https://www.dw.com/en/bolivias-evo-morales-plans-Lithium-mining-offensive/a-39727810.

This is not to discount the economic potential from the implementation of grand projects such as that proposed in Bolivia. However, at the outset, it is important to stress the currently small-scale nature of markets like lithium and cobalt (as well as others such as graphite and rare earths) compared to the more established materials copper, iron, gold and coal, as well as the role played by EVs compared with traditional end uses such as the manufacture of steel alloys for the construction sector in the demand for zinc, manganese, nickel or chrome. However, there remains substantial growth potential, especially for countries and territories with relevant endowments and feature one or more large assets (especially where their values are high relative to the scale of the overall economy) and where production could be materially expanded or newly commercialised.

Importantly, any economic or fiscal projections related to the development of EV raw material industries needs to have a realistic outlook for market growth, domestic industry penetration in international markets and the potential value and hence profitability (see Jones (2019) for a discussion of revenue forecasting issues in mineral sectors). If a country is to avoid boom-bust investment cycles and the risk of inefficient spending there needs to be a data-driven and suitable risk-based approach grounded in the commercial realities of the key domestic assets and projects as well as an understanding of the drivers and risk factors shaping the evolution of the market and competitor landscape,

In particular, fast-growing markets where new investments will be needed to satisfy demand, warrant particularly close scrutiny on the likely investment requirements, and their implications for the scale, timing and profitability of any capacity development or expansion. In the case of the lithium industry, the additional capital intensity of brine-based production (despite low operating costs) has been among a range of factors which have hindered expansion of production in Latin American, with more rapid investment growth observed in hard rock mining projects in Australia (which typically have lower initial capital costs, and shorter project lead times). This highlights the importance of understanding the trade-offs between capital and operating costs and the implications for competitiveness and the associated economic and fiscal indicators over different term horizons.

Understanding international price mechanisms is also important for the formulation of economic projections (including the valuation of exports and estimating domestic industry profitability). This typically warrants a particular focus on the locus and production costs of international 'swing producers' in any market (these are usually the highest cost sources of production whose commercial viability is most acutely exposed to price fluctuations).[14] These are likely to include Chinese lithium producers, (artisanal) cobalt miners in the DRC and smaller scale South African miners of manganese.

4.4 | Strengthening tax administration

For developing countries, the EV revolution offers considerable upside opportunities for fiscal revenues, but also potentially increases the challenges to effective tax administration. This is due to a range of factors, including the lack of widely available market prices for many battery minerals and associated beneficiated products, the fundamental complexity and opacity of these value chains, as well as

[14]In some cases, however, 'swing' production does not always come from the highest cost producers. Notably in manganese, swing production is increasingly concentrated in small scale, often third quartile, producers, rather than larger scale, and more expensive, fourth quartile producers due to the greater prevalence of longer term 'take or pay' contract structures with Asian buyers.

the trend towards more vertically integrated industries and the associated increase in the frequency and value of internal transactions.[15]

A number of these issues are evident from recent disagreements regarding tax payments between a number of governments and major lithium producers. For example, in 2018 Chile's government announced the creation of a committee to supervise lithium contracts following allegations that US-based Albemarle was charging below-market-prices for its sales to foreign affiliates. The absence of clear market pricing for many of these minerals impedes the capacity of governments to evaluate taxable values.

Such challenges and risks are exacerbated by vertical integration in many industries, which increases the prevalence of, and fiscal risks associated with, transactions between related parties. In Ghana, for example, the Ministry of Lands and Natural Resources have instructed a detailed technical and financial audit of the plans and financial practices of a major manganese producers following its acquisition by a Chinese producer. Such action reflected concerns regarding, not only excessive scaling up of mine production plans (putting pressure on local infrastructure), but also the associated tax revenues (the unit price of manganese ore exports from Ghana over the 2016–2018 remained flat while global benchmark prices over the same period almost doubled). In August 2019, the government stopped all operations with immediate effect after several infractions were found upon the completion of these preliminary technical and financial audits.

Looking to the future, mitigating the potential fiscal risks in these and other relevant examples is likely to require investment in robust transfer pricing rules. One potentially desirable option is to establish an 'arms-length' pricing formula that estimates the value of a given raw material as a function of market conditions, and the technical characteristics of the ore or beneficiated product in question (considering grades, impurity levels etc.). However, implementing such pricing rules may be technically challenging given the opacity and complexity of some battery raw materials chains. One particular issue concerns potential differences in taxable value which can exist across product segments. The manganese example cited earlier is a good case in point. While the majority of ore extracted is almost certainly used for ferro manganese and other steel alloying purposes, battery cathode manufacturers have created a small but growing demand for highly valuable metal and chemical based derivates. Addressing these issues requires an understanding not only of prices in these new niche segments but also of their scale (since the later end use in this case can be easily saturated, potentially leading to an overestimation of total offtake value).

Moreover, the fiscal and investment risks associated with mis-specified pricing formula are significant. At the same time, however, the requisite skills and data for the effective mitigation of these issues and risks are rarely found in the public sector, requiring specific technical inputs by experts in raw materials markets and pricing. Thus, effective institutional capacity development is likely to require closer cooperation between policymakers, international financing agencies, as well as industry practitioners and data providers in the provision of relevant technical support services.

4.5 | Negotiation and marketing support

China, South Korea and Japan currently dominate battery and components manufacturing as well as associated chemicals refining. Market concentration of this type risks weakening the terms of trade for developing country exporters, particularly where producers are small in scale or lack understanding

[15]Beneficiation is the treatment of raw materials to improve the chemical or physical properties usually prior to smelting. For example, for coal beneficiation involves separating inorganic impurities from the raw coal.

and awareness of the broader international markets. In the DRC, for example, ASM miners sell the majority of their cobalt to (largely Chinese) traders and are commonly required to accept large discounts (perhaps even as high as 75%) relative to market prices. These trends are not limited to battery-related end uses and customers. In the case of manganese the emergence of 'super smelters', largely in Indonesia and China, has gradually weakened the negotiating power of (particularly smaller scale) South African producers.

Collectivisation has traditionally been a central response to such circumstances and may have some merits: for example, by creating the necessary scale to support investment in early-stage processing technologies (payables on higher grade cobalt ores, e.g. may increase disproportionately on a contained basis compared to lower grades). These opportunities may also extend to marketing. For example, individual cobalt miners in the DRC commonly pool their product prior to on-sale to traders. The government is now planning to go further. In November 2019, the government created the Entreprise Generale du Cobalt as a subsidiary of state mining company Gecamines to purchase and market all cobalt that is not mined industrially as a way to exert greater influence over prices. With this company only newly operational at time of writing, the outcomes remain unclear.

However, international experience with such national mineral marketing agencies has been mixed. While there may be opportunities to increase the effectiveness of marketing and encourage formalisation of an ASM industry segment, such entities may also be at risk of succumbing to executive pressures for its operations to help support wider foreign policy objectives or domestic political goals, including as a mechanism for delivering patronage through appointments to executive positions (or corruption through opportunities to sell materials at below market prices). As such, any state marketing company is likely to benefit from independent market advice and strong governance arrangements to enable it to create value and avoid these common pitfalls.

4.6 | Beneficiation and other downstream processing

A key strategic question for all major natural resource exporters is where in the value chain to target production and investment. In this context, there is often substantial pressure to prioritise the advancement of beneficiation capacity among developing country governments and industry participants. This largely reflects the belief that such investments are a pathway to more rapid economic development, greater and higher skilled employment, as well as stronger industrial and technical spillovers. For example, the Indonesian government has recently placed significant pressure on Freeport-McMoRan to invest in a domestic copper smelter in return for an enhanced social licence to operate at a major copper mine in the country.

In practice, however, such strategic questions warrant careful consideration on an industry- and country-specific basis, taking account of both the locus of value within any mineral production and processing chain and the existence of (or potential for fostering) sufficient comparative advantage to sustain profitability and market share in any given downstream segment. This later point can be a function of a wide variety of factors, including resource and factor endowments, enabling conditions (such as port and logistics facilities and sufficiently abundant low-cost power), as well as access to downstream markets and customers.

Importantly, the distribution of value added differs across commodity chains. In the case of some traditional markets, particularly those in which fundamental resource scarcity or quality-related rents exist, economic value added tends to be concentrated in upstream value segments. This is the case for copper where mining costs are commonly in the range of 2000–5000 USD per tonne of contained metal, compared with prices which generally range from 6000 to 10,000 USD per tonne. These levels of 'structural' profitability are in stark contrast to the narrow treatment and recovery charges typically earned by downstream smelters and refiners.

In contrast, value is likely to more heavily distributed in the mid and downstream segments in battery raw materials. In lithium, for example, spodumene (a lightly processed ore typically containing 5–8% mineral by weight) has a (much elevated) sale value in March 2022 of approximately 2500 USD per tonne. However, lithium carbonate and lithium hydroxide, substantially purer chemical derivatives, are currently valued anywhere in the region of 50,000–70,000 USD per tonne. These marked value increments have fuelled a lively debate among policymakers in many exporting countries around the world regarding the potential to increase domestic value retention through policies designed to stimulate investment in downstream processing.

A variety of policy strategies have been employed in an effort to realise incremental value. In the case of Western Australia, for example the lithium royalty regime was actively adjusted to encourage beneficiation into lithium chemicals. In other markets, governments have pursued more interventionist policies. Indonesia, for example has sought to stimulate investment in domestic processing by actively banning the export of unprocessed ores, such as nickel (and through support for commercial partnerships with Chinese investors). This later approach has proved fairly successful in fostering the significant expansion of domestic nickel smelting and integrated stainless-steel manufacturing capacity (and associated industrial clusters), but the effects of these policies cannot be readily disassociated from the existence of real domestic comparative advantages afforded by close proximity to Chinese steel and alloy manufacturers (established investor relationships), sufficient low cost (coal based) power and access to (and an oligopolistic position in international markets for) primary feedstocks.

However, downstream battery cluster development is likely to face quite different challenges on the continents of Africa and Latin America. The absence of a large, domestic or geographically proximate, demand centre is a disadvantage. Physical access to customers is typically an important driver of commercial success in downstream markets, particularly in the manufacture of battery chemicals given that they have the tendency to absorb water in the atmosphere during transportation (substantially complicating their subsequent downstream processing).[16] Beyond this, a particular consideration for downstream value chain development in Africa concerns the importance of sufficient and low-cost power. Deficiencies in power provision, reliability and cost have contributed to declining beneficiation industries (including in manganese, chrome and silicon) in South Africa, for example (and hindered development and competitiveness of the mining industries more generally across the continent). Weaknesses in transportation infrastructure has also proved to be a critical barrier, particularly in the upstream sector where, too often, bulk ores are trucked at high costs over long distances on poorly surfaced and maintained roads. Neither are these issues limited to Africa: key segments of the 'lithium triangle' in South America, including in Bolivia and remote North-Western regions of Argentina, are critically encumbered by weak transportation infrastructure, limited access to a skilled labour force and other key factors of production, undermining the potential to produce cost-effective primary materials which are critical preconditions for value chain development.

4.7 | Environmental, social and governance risks and opportunities

Demand for EVs is associated with broader trends towards the pursuit of higher ESG standards in the extractives industries. Social issues arising from the extraction of cobalt in the DRC, for example, have

[16]Other physio-chemical properties may favour localisation of end-of-life chain development: the transportation of spent batteries present significant fire hazards due to the risk short circuits.

been a foremost concern to date given the widespread environmental damage and human rights abuses associated unregulated artisanal mining (including child labour, lack of workplace safety and forced relocation of villages) (Amnesty International, 2016). These issues have encouraged efforts to ensure more responsible sourcing among buyers, producers and traders.

Since 2018 the London Metal Exchange requires all traded cobalt traded to undertake an audit assessment of the compliance of material with OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas, or equivalent. Major buyers of cobalt, including Apple, VW and Tesla are reforming their purchasing rules to ensure that all metal procured satisfies high ethical and environmental standards. In May 2020, in perhaps a bell weather decision, Huayou Cobalt, China's biggest cobalt producer, decided to stop buying from artisanal producers due to pressure over the use of child labour in DRC's informal mining sector.

These trends present both risks and opportunities for developing countries. Clearly, higher standards of environmental and social protection have the potential to confer material benefits on many, often highly vulnerable, households and communities. However, a failure to take effective action to ensure compliance with emerging standards risks undermining their future market access (thereby risking the function of an important social security net in many rural areas within resource-rich developing countries). Tesla, for example, has diverted its procurement of cobalt away from DRC towards Australia in an effort to mitigate such risks. Whether this is sustainable in the presence of long-term growth trajectories and existing supply side constraints in developed countries is unclear and, if enough buyers follow suit, may even require the payment of a premium above the relevant price benchmark given the scarcity of ex-DRC supplies.

Policies aimed at both formalising, and verifying environmental and social standards associated with, artisanal mining are a clear priority. To achieve effective policymaking requires improved government effectiveness, including enhanced governance and transparency frameworks. Among a wide variety of policies and programmes to support these goals have been recent efforts in DRC to collectivise and organise artisanal cobalt miners around larger scale pits with better safety rules and access to equipment, coupled with the necessary tracing equipment to ensure these enhanced standards can be verified by international buyers.

Such issues are not restricted to cobalt. The production of lithium from brines is associated with large scale exploitation of scarce water resources (and is subsequently exposed to solar evaporation in order to recover the unprocessed mineral). This is a critical issue in the water scarce Atacama Desert, affecting local farmers and communities. The two principal mining companies operating in the region are estimated to extract around 63 billion litres of water a year.[17] Water concerns are already shaping the evolution of the industry. The Chilean government, for example has restricted the production quotas of the major industry participants as a direct response and producers are increasingly compensating local communities for these damages. The successful development of more water-efficient extractive processes is likely to be essential to sustain the industries future social licence to operate in such an environmentally fragile setting.

Nickel refining is another case of a battery value chain resulting in substantial environmental costs and risks. Disregarding for a moment the highly energy-intensive nature of the production process, converting low grade nickel laterite ores into a highly purified battery grade nickel produces large amounts of waste, which in turn requires careful storage. Recent nickel-refining projects, including in Indonesia, have proposed to dispose of the waste in deep sea repositories. Such an approach is controversial and there have been widespread calls for its discontinuation, given the threat to local coral reefs

[17]See https://www.dw.com/en/Lithium-extraction-for-e-mobility-robs-chilean-communities-of-water/a-51844854.

and fish stocks from failures in tailings management. Such an environmental disaster occurred in 2019 at a nickel and cobalt processing facility in Papua New Guinea.

As such, growth in the production of EVs risks exacerbating environmental externalities associated with the manufacture of their raw materials. This reinforces the need for effective fiscal and regulatory policies to mitigate environmental and social risks associated with mining and metal processing in parallel with measures to promote EV diffusion. Targeted measures to mitigate upwards pressures on greenhouse gas emissions by the industry is a case in point. Already investors and policymakers are beginning to respond to these challenges. Anglo American, for example a leading international miner, is planning to decarbonise power supplies to its entire Latin American Copper operations by 2023. However, more will be needed to decarbonise an industry which consumes a large percentage of power in resource-rich countries and is often reliant on inefficient diesel and back-up generation in remote locations, particularly in Africa (Arena, 2017).

To this end, robust, credible economy-wide carbon pricing has the potential to further catalyse the shift towards lower carbon mining. However, sector-specific measures may also be required to overcome technological and informational barriers to sector transformation: CORFO, the Chilean mining ministry and development agency, for example, is setting up a special technological institute to encourage solar energy and low emission mining and advanced materials of lithium and other minerals.[18] Governments may also help to coordinate producers with renewable power service providers to instal shared facilities in order to help overcome adoption barriers faced by short and late life mine operators (that may not be able to commit alone to longer term renewable contracts for example).

5 | CONCLUSIONS

Effective management of the natural resources sector presents a range policy issues, and positive macroeconomic and broader developmental outcomes from natural resource endowments are far from assured. However, empirical evidence on the resource curse increasingly points to the importance of strong institutions and capacity to help limit the risk of inefficient and mistimed public investment, and adapt to industry procyclicality, which can foster boom-bust cycles, debt overhang and credit market issues (see, e.g. Aghion et al., 2009; Manzano & Ribogon, 2001).

These issues are particularly relevant in the context of a potential boom in EV-related raw materials, many of which suffer from weaker liquidity and more market opacity. The recovery from the COVID-19 downcycle has seen increased commodity prices particularly in EV materials markets. The prospect of spiralling demand for raw materials such as lithium and cobalt has fuelled widespread optimism among developing country exporters.

Countries are also increasingly adapting policies to capture a larger share of the resulting value generated. However, as is well known, the existence of known deposits is no guarantee of future domestic resource mobilisation. Careful policy management will be required to successfully expand EV- and battery-related resource mobilisation.

A key issue hindering economic and sector policy development is the deep uncertainty surrounding the rate and depth of this transformation. A sound understanding of the outlook for, and drivers of, demand growth is important in exploiting economic opportunities and mitigating risks associated with industry procyclicality. Our analysis highlights the critical importance of monitoring and evaluating

[18] https://www.oecd.org/dev/Corfo-Session_7_Chilean-Clean_Technologies_Institute.pdf.

the impacts of cell and broader EV manufacturing costs, as well as deployment policies in China as part of efforts to develop informed and suitably 'risked' views on future market transformation.

The growth in EVs, and the disproportionately large share of value that is currently earned in the mid and downstream value segments, is stimulating age-old, and often rather vexed, questions regarding the potential for greater downstream processing as part of national development strategies. These require a clear understanding of the sources of comparative advantage associated with, and the potential barriers to, greater domestic vertical integration and value chain development. In particular, while countries such as Indonesia have observed some successes in terms of downstream value chain development (including with support from rather unconventional policy levers), a lack of abundant low-cost power, technical knowhow and/ or access to major consuming markets may limit the potential for successful in other developing country settings, particularly in Africa.

Bolstering enabling conditions for industry expansion and associated development benefits requires a broad range of complementary policies including (1) increased priority to geological research and early stage prospecting into new ore bodies that may host battery materials; (2) strengthening of tax administration and mineral marketing capacity and (3) measures to mitigate a range of possible adverse environmental and social impacts associated with lithium, cobalt and nickel mining, processing and recycling.

Finally, reforms designed to delivery higher ESG standards may also be required to preserve access to developed county markets, particularly in consumer facing end uses such as automotives. These have the potential to confer material benefits on many, often highly vulnerable, households and communities. Their implementation is likely to require an increasingly sharp focus, not only on measures to bolster social and local environmental standards but also on both economy wide and sector specific enabling policies and measures to help decarbonisation of the mining industry.

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DATA AVAILABILITY STATEMENT

Data for the model can be made available and is open source.

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REFERENCES

Addison, A. (2018). Climate change and the extractive sector, WIDER working paper 2018/84.

Aghion, P., Bacchetta, P., Rancière, R., & Rogoff, K. (2009). Exchange rate volatility and productivity growth: The role of financial development. *Journal of Monetary Economics*, *56*(4), 494–513.

Amnesty International. (2016). *This is what we die for: Human rights abuses in the DRC power the global trade in cobalt*. Amnesty International.

Antras, P., & Chor, D. (2013). Organizing the global value chain. *Econometrica*, *81*(6), 21227–22204.

Antras, P., & de Gortari, A. (2020). On the geography of global value chains. *Econometrica*, *84*(4), 1553–1598.

Arena (2017). Renewable Energy in the Australian Mining Sector: White paper. https://arena.gov.au/assets/2017/11/renewable-energy-in-the-australian-mining-sector.pdf

Auty, R.M. (1993), *Sustaining development in mineral economies: The resource curse thesis, Routledge, London*.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H. E., & Heidrich, O. (2021). Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. *Nature Sustainability*, *4*, 71–79. https://doi.org/10.1038/s41893-020-00607-0

Baldwin, R. (2016). *The great convergence: Information technology and the new globalization*. Harvard University Press.

Boschini, A. D., Pettersson, J., & Roine, J. (2007). Resource curse or not: A question of appropriability. *Scandinavian Journal of Economics*, *109*, 593–617.

Coe, N. M., & Yeung, H. (2015). *Global production networks: Theorizing economic development in an interconnected world*. Oxford University Press.

Costinot, A., Vogel, J., & Wang, S. (2013). An elementary theory of global supply chains. *Review of Economic Studies*, *80*, 109–144.

Criscuolo, C., & Timmis, J. (2017). The relationship between global value chains and productivity. *International Productivity Monitor*, *32*, 61–83.

Eggert, R., Wadia, C., Anderson, C., Bauer, D., Fields, F., Meinert, L., & Taylor, P. (2016). Rare earths: Market disruption, innovation and global supply chains. *Annual Review of Environment and Resources*, *41*(10), 1–10.

EU Commission (2019). REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK on the Implementation of the Strategic Action Plan on Batteries: Building a Strategic Battery Value Chain in Europe COM/2019/176 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1554816272501&uri=COM:2019:176:FIN

Fally, T., & Hillbery, R. (2018). A Coasian model of international production chains. *Journal of International Economics*, *114*, 299–315.

Frankel, J.A. (2010). The natural resource curse: A survey, *NBER working paper 15836, Cambridge, MA*. https://www.nber.org/papers/w15836

Gelg, A. and associates. (1988). *Oil windfalls: Blessing or a curse?* Oxford University Press.

Gilerthorpe, E., & Papyrakis, E. (2015). The extractive industries and development: The resource curse at the micro, meso and macro levels. *Extractive Industries and Society*, *2*, 381–390.

Government of Western Australia (2019). Future Battery Industry Strategy Western Australia. https://www.jtsi.wa.gov.au/docs/default-source/default-document-library/future-battery-industry-strategy-wa-0119.pdf?sfvrsn=ccc7731c_6

Habib, K., Hamelin, L., & Wenzel, H. (2016). A dynamic perspective of the geopolitical supply risk of metals. *Journal of Cleaner Production*, *133*, 850–858.

Hagman, J., Ritzén, S., Stier, J. J., & Susilo, Y. (2016). Total cost of ownership and its potential implications for battery electric vehicle diffusion. *Research in Transportation Business & Management*, *18*, 11–17.

Hummels, D., Ishii, J., & Yi, K.-M. (2001). The nature and growth of vertical specialization in world trade. *Journal of International Economics*, *54*, 75–96.

IEA. (2017). *Renewables 2017: Analysis and forecasts to 2022*. IEA.

IEA (2021a). Global EV Outlook.

IEA (2021b), *The role of critical minerals in clean energy transitions*. IEA. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

Jones, B. (2019). Revenue forecasting in the mining industries: a data-driven approach.

Jones, B., Nguyen, T., & Elliott, R. (2020). The EV revolution: The road ahead for critical raw materials demand. *Applied Energy*, *280*, 115072.

Lebedeva, N., Di Persio, F., & Boon-Brett, L. (2017). *Lithium ion battery value chain and related opportunities for Europe. JRC Science for Policy Report*. Publications Office of the European Union.

Lévay, P. Z., Drossinos, Y., & Thiel, C. (2017). The effect of fiscal incentives on market penetration of electric vehicles: A pairwise comparison of total cost of ownership. *Energy Policy*, *105*, 524–533.

Manzano, O., & Ribogon, R. (2001). *Resource curse or debt overhang? Working paper 8390*. NBER.

Mayyas, A., Steward, D., & Mann, M. (2019). The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. *Sustainable Materials and Technologies*, *19*, e00087.

Mehlum, H., Moene, K., & Torvik, R. (2006a). Cursed by resources or institutions? *The World Economy*, *29*(8), 1117–1131.

Mehlum, H., Moene, K., & Torvik, R. (2006b). Institutions and the resource curse. *Economic Journal*, *116*, 1–20.

NREL (2019). Supply chain of Raw Materials used in the Manufacturing of Light-Duty Vehicle Lithium Ion Batteries. https://www.nrel.gov/docs/fy19osti/73374.pdf

Olivetti, E. A., Cedar, G., Gaustad, G. G., & Fu, X. (2017). Lithium-ion battery supply chain considerations: Analysis of potential bottlenecks in critical metals. *Joule*, *1*, 229–243.

Redlinger, M., & Eggert, R. (2016). Volatility of by-product metal and mineral prices. *Resources Policy*, *47*(C), 69–77.

Reuters. (2021). Column: U.S. infrastructure bill targets critical minerals supply. https://www.reuters.com/article/us-critical-minerals-ahome/column-u-s-infrastructure-bill-targets-critical-minerals-supply-idUSKBN2FD1GU

Rodrik, D. (2016). Premature deindustrialization. *Journal of Economic Growth*, *21*, 1–33.

Ross, M. (2014). *What have we learned about the resource curse?* University of California.

Taglioni, D., & Winkler, D. (2016). *Making global value chains work for development*. The World Bank.

Tisserant, A., & Pauliuk, S. (2016). Matching global cobalt demand under different scenarios for co-production and mining attractiveness. *Journal of Economic Structures*, *5*, 4.

US Department of Energy (2020). Critical Materials Rare Earths Supply Chain: A situational white paper. https://www.energy.gov/sites/prod/files/2020/04/f73/Critical%20Materials%20Supply%20Chain%20White%20Paper%20April%202020.pdf

USGS (U.S. Geological Survey) (2020a). 'Lithium Commodity Summary 2020'. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-Lithium.pdf

USGS (U.S. Geological Survey) (2020b). 'Cobalt Commodity Summary 2020'. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-Cobalt.pdf

USGS (U.S. Geological Survey) (2022). 'Mineral Commodity Summaries 2022'. https://pubs.er.usgs.gov/publication/mcs2022

World Bank. (2017). *The growing role of minerals and metals for a low carbon*. World Bank.

World Bank. (2020). *Minerals for climate action: The mineral intensity of the clean energy transition*. World Bank.

Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., & Steubing, B. (2020). Future material demand for automotive lithium-based batteries. *Communications Materials*, *1*(1), 1–10.

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