# Reviewing the material and metal security of low-carbon energy transitions

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# Reviewing the material and metal security of low-carbon energy transitions

Lee, J.[1], Bazilian, M.[1], Sovacool, B.[2], Hund, K.[3], Jowitt, S. M. [4], Nguyen, T.P. [3], Månberger, A.[5], Kah, M. [6], Greene, S. [7], Galeazzi, C. [8], Awuah-Offei, K.[9] , Moats, M.[10], Tilton, J. [1], Kukoda, S.[11]

[1] The Payne Institute for Public Policy, Colorado School of Mines, 816 15th St. Golden, CO, USA
[2] University of Sussex Business School, Jubilee Building, 9SL, Falmer, Brighton, United Kingdom
[3] Energy and Extractives Global Practice, World Bank, 1818 H Street, NW Washington, DC, USA
[4] Department of Geoscience, University of Nevada Las Vegas, 4505 S Maryland Pkwy, Las Vegas, NV, USA
[5] Environmental and Energy Systems Studies, Lund University, Box 117, SE-221 00, Lund, Sweden
[6] Center on Global Energy Policy, Columbia University, 116th St & Broadway, New York, NY, USA
[7] Center for Transportation & Logistics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA
[8] Centre for Energy, Environment, and Natural Resource Governance, Department of Land Economy, University of Cambridge, The Old Schools, Trinity Ln, Cambridge CB2 1TN, United Kingdom
[9] Mining & Nuclear Engineering, Missouri University of Science & Technology, 280 McNutt Hall, Rolla, MO, USA
[10] Department of Metallurgical Engineering, Missouri University of S&T, Parker Hall, 106, 300 W 13th St, Rolla, MO, USA
[11] International Copper Association, 799 9th St NW, Suite 1000, Washington, DC, USA

**Abstract:** The global transition to a low-carbon economy will involve changes in material markets and supply chains on a hitherto unknown scale and scope. With these changes come numerous challenges and opportunities related to supply chain security and sustainability. To help support decision-making as well as future research, this study employs a problem-oriented perspective while reviewing academic publications, technical reports, legal documents, and published industry data to highlight the increasingly interconnected nature of material needs and geopolitical change. The paper considers a broad set of issues including technologies, material supplies, investment strategies, communal concerns, innovations, modeling considerations, and policy trends to help contextualize policy decisions and regulatory responses. Policy options are outlined for each topical section, as well as areas for further research. Together, these recommendations serve to help guide the complex, interdisciplinary approach to materials required for a low-carbon transition.

**Keywords***:* Energy transitions; Critical materials; Critical resources

Declarations of interest: none

<u>Abbreviations</u>:

EVs - electric vehicles
PV - photovoltaic
LIB - lithium-ion batteries
LCO - lithium cobalt oxide
NCM - nickel cobalt manganese
LFP - lithium iron phosphate
REE - rare earth elements
c-SI - crystalline silicon
CIGS - copper indium gallium selenide
CdTe - cadmium telluride
DSSC - dye sensitive solar cells
PMG - permanent magnet generator
CSP - concentrated solar power
GW - gigawatt
DRC - Democratic Republic of the Congo

BRI - Belt and Road Initiative
NDC - nationally determined contribution
STRADE - Strategic Dialogue on Sustainable Raw Materials
SOE - state owned enterprises
HREE - heavy rare earth elements
LREE - light rare earth elements
PGM - platinum group metals
RGI - resource governance index
NRGI - Natural Resource Governance Institute
IISD - International Institute for Sustainable Development
ASM - artisanal or small scale mining
ILO - International Labor Organization
Ton - 2000 pounds

## 1. Introduction

With the nearly global commitment to the 2015 UNFCCC Paris Agreement, and an ever-increasing portion of global energy consumption coming from renewable sources, the low-carbon nature of the world's energy supply is solidifying [1]. The increased use of solar photovoltaics, battery storage, and wind energy in particular have proven the economic and technical feasibility of renewables. Reports and forecasts examining the general pace and requirements of this energy transition (e.g., [2]–[7]) have demonstrated the contours of the shift, but have also raised concerns regarding its mineral and metal requirements [2]–[7].

Low-carbon scenarios often have—implicitly or explicitly—high and diverse material needs, depending on what assumptions are made about the nature of future energy systems. As certain technologies become more prominent, it becomes easier to identify what materials will be needed in the near term [2]. Limitations on these materials, along with competition for large portions of commonly produced materials, may inhibit the adoption of "game changing" technologies that are often considered vital to a nation's economic prosperity. The materials that have proven valuable in supporting the development of low-carbon technology are often listed alongside other "critical" materials (e.g., [8], [9]) and are central to the feasibility of the energy transition [8], [9]. Supply risks, stemming from geopolitical or environmental instability, along with sudden, unmanageable increases in demand for more commonly produced materials, can be detrimental to a nation's economic prosperity. The relationship between supply risk and economic importance has been explored by the European Commission and by various countries and organizations around the world. [8].

More focused investigations into specific minerals and metals (e.g., [10]–[14]) provide insight into the feasibility of meeting renewable energy requirements, but do not typically explore non-technical considerations such as investments, trade barriers, or geopolitical challenges [10]–[14]. With these considerations in mind, what material changes are necessary to achieve a renewable energy system, and how can policies support these changes? Equally importantly, what environmental, social, and political challenges are associated with low-carbon technologies, and how can they impact material supplies? To address these concerns, this review focuses on both grey and academic literature, especially those focused on energy outlooks and low-carbon technology, makes recommendations for policy interventions that could address these concerns, and highlights areas that require future research.

This paper is divided up into several sections that each focus on a different aspect of the material requirements for the transition to lower CO2 energy systems (hereafter termed the energy transition). Section 2 provides an overview of prominent renewable energy technologies and their material concerns, with Section 3 discussing the role of physical scarcity in material considerations. Section 4 provides an overview of investment trends in the United States and China, along with possible implications for their impact on the energy transition. Section 5 focuses on the role of local communities and developing nations in material supply chains and the energy transition. Section 6 discusses how technical changes can influence the supply chain, and how material concerns can be mitigated. Section 7 provides context to economic discussions and potential shortcomings of economic forecasts, and Section 8 provides an overview of policy learning and political trends. Finally, Section 9 provides conclusions and identifies key areas for future research.

## 2. Low-Carbon Technologies

This section examines the material needs for the increased uptake of prominent renewable technologies, alongside market trends and future material projections. We focus on electric vehicles (EVs), solar Photovoltaics (PV), and wind energy, as they are commonly recognized as the cornerstones of the transition to low carbon energy.

### *2.1 Electric Vehicles: Motors and Battery Storage*

For energy storage and electric vehicles, lithium ion batteries (LIB) are a technological focus. There are several chemical variations of LIBs that differ with respect to their properties and stability. Currently, the most prominent EV and battery storage compositions are lithium-cobalt-oxide (LCO), nickel-cobalt-manganese (NCM) and lithium-iron-phosphorus (LFP) [2], [10], [15], [16]. Lithium is used for electrolyte and anode productions, whereas copper, aluminum, and steel are used for various processes and assembly needs (Figure 1). The cathode is traditionally a layered transition-metal oxide composed of lithium compounds with cobalt, manganese, nickel, phosphorus, and iron [17], [18]. The rare earth elements (REE) neodymium and dysprosium are also used in electric motors' permanent magnets to improve performance [2].

Due to its variety of technologies and rapid development, energy storage is among the most difficult of energy markets to predict. NCM batteries are becoming increasingly popular thanks to their wide range of power output and a steep decline in costs (84%) since 2010 [5]. As the world's largest consumer of lithium, China has traditionally used LFP batteries for a variety of purposes, including electric buses, but NCM variations are still expected to control 90% of the market share by 2025–30 [15], [19]. Following the adoption of NCM batteries, and EVs becoming the lower cost option in 5-10 years, Bloomberg's New Energy Outlook 2019 envisions electric vehicles adding about 3,950TWh of new electricity demand globally by 2050 and using 9% of the world's electricity [5], [18]. However, from a production perspective, the World Bank estimates that a 1000% increase in cumulative material demand is expected from the rollout of energy storage technologies if the number of electric vehicles reaches 140 million by 2030 (Figure 2) [2].

Critical energy storage materials in batteries include lithium, cobalt, and nickel, and in motors, neodymium, and dysprosium. Highly publicized concerns about child labor in artisanal cobalt mines in the Democratic Republic of the Congo, and the doubling of the royalty rate on cobalt in DRC in 2018, has generated a drive for EV suppliers to develop cobalt-free batteries in the near future [20]. An NCM battery with a 1-1-1- ratio has the highest cobalt usage but the lowest energy density, whereas an NCM battery with a 8-1-1 ratio has the lowest cobalt usage, but the highest energy density. This means that although 8-1-1 NCM batteries have additional production costs and greater cell degradation (from the lack of stabilizing cobalt), they may well represent the next generation of cathodes as a result of increased capacity and lower cobalt content. However, the development of 8-1-1 NCM batteries has occurred at a slower pace than expected [21], [22]. Moores (2018) terms this *the* classic battle between the benefits of an existing supply chain and the energy density of new battery developments. In other words, these developments represent a contest between the three criteria of supply chain: security, battery performance, and cost [22]. It is possible to develop completely cobalt-free lithium batteries, but industry experts doubt their feasibility in the near term [20], [23], [24]. Månberger et. al (2018) and Giurco et. al. (2019) both put demand for cobalt at over 400% of current reserves[1] by 2050, with lithium demand also exceeding 100% of reserves, assuming no major reductions in metal intensity take place [7], [11]. Recycling opportunities for lithium batteries offer mitigating effects due to existing collection channels for lead-acid vehicle batteries [18]. From this, Dominish et al. (2019) state that the recycling rate for cobalt and nickel have the potential to be close to 90% if suitable recycling industries scale up their operations, despite current recycling rates being nowhere near this level [18]. Reports on lithium recycling currently vary from 0-10%, although rates have the potential to increase with demand [9], [18].

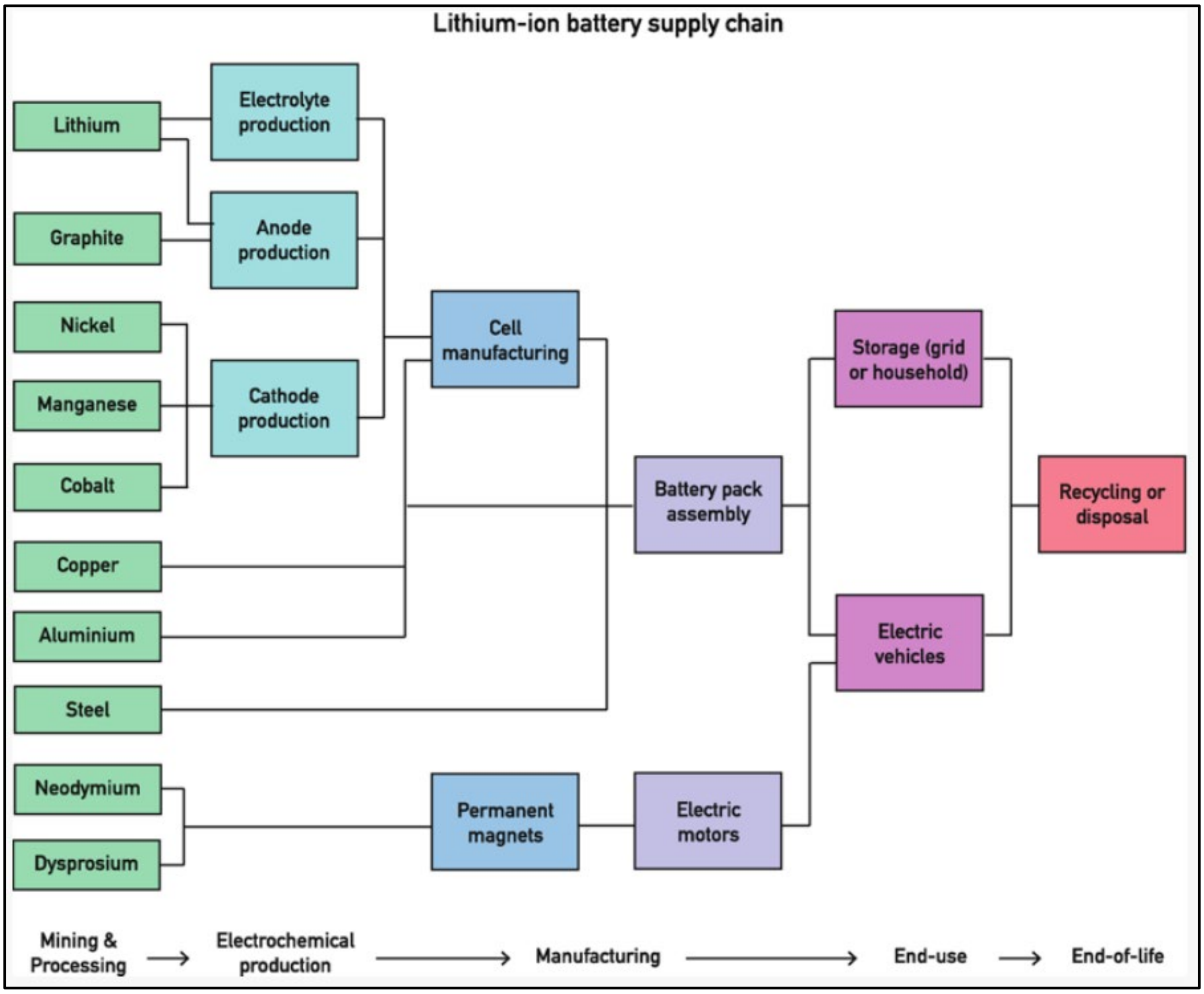



**Figure 1: Overview of lithium-ion battery supply chain**
(Giurco et al. 2019)

[1] Reserves are often 20% of resources or less, a function of investment, and should not be used as an indicator of long-term availability. Reserve values instead serve to contrast potential needs against the current economic production of minerals.

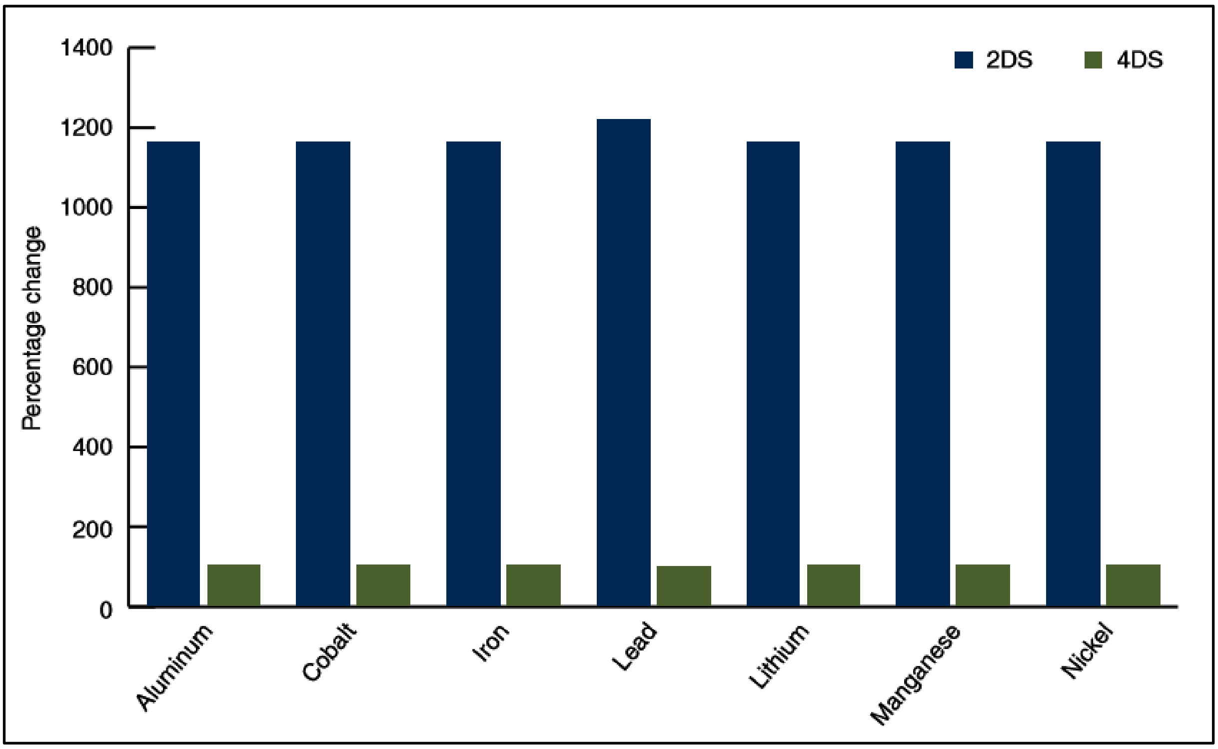



**Figure 2: Median metals demand scenario for supplying energy storage technologies through 2050**
(World Bank 2017)

*2.2 Solar Photovoltaics (PV)*

Of the two types of PV panels used today, crystalline silicon (c-Si) PV panels account for approximately 95% of the global market [7]. By weight, a typical panel is composed of 76% glass, 5% silicon solar cells, 10% polymer that acts as an encapsulant and backsheet, 8% aluminum as a lightweight frame, 1% copper for interconnectors, less than 0.1% silver for contact lines, and trace amounts of other metals [25] (Figure 3).

Thin film technologies, copper-indium-gallium-selenide (CIGS) panels, and cadmium telluride (CdTe) account for the remainder of the market. The uncertainties around tellurium supply, and the supposed toxic nature of handling cadmium have raised concerns with thin film technologies, and it is not clear what the role of CdTe will be in the future [9],[26], [27]. There are also several solar PV technologies currently at the research stage, such as dye-sensitized solar cells (DSSC)/Grätzel-cells and perovskites that use other metals than current PV technologies [11],[28], [29]. These technologies could have a decisive impact on future metal used in solar PVs, but it remains uncertain whether they will be commercialized or not.

Although the amount of material used in each solar panel has decreased since commercialization, silver still accounts for 20% of the panel value and is not consistently recycled due to process constraints [18], [30]. According to the International Technology Roadmap for Photovoltaics, silver consumption is expected to further decrease due to better metallization processes and substitution with copper or nickel/copper layers, but the changes will reach <15% of the market by 2028 [31]. The importance of recycling is highlighted by preliminary estimates that the raw materials recoverable from PV panels could cumulatively exceed USD 15 billion by 2050 [25]. For material needs, the World Bank estimates median metals demand for supplying solar photovoltaics through 2050 to increase by □150% to □300% for 2°C and 4°C climate mitigation scenarios [2], [25]. Silver demand is of specific concern, as shown in Figure 4, with estimates by Watari et. al (2018) and Valero et. al (2018) both putting demand for silver at  70% of current reserves by 2050 [14], [32].

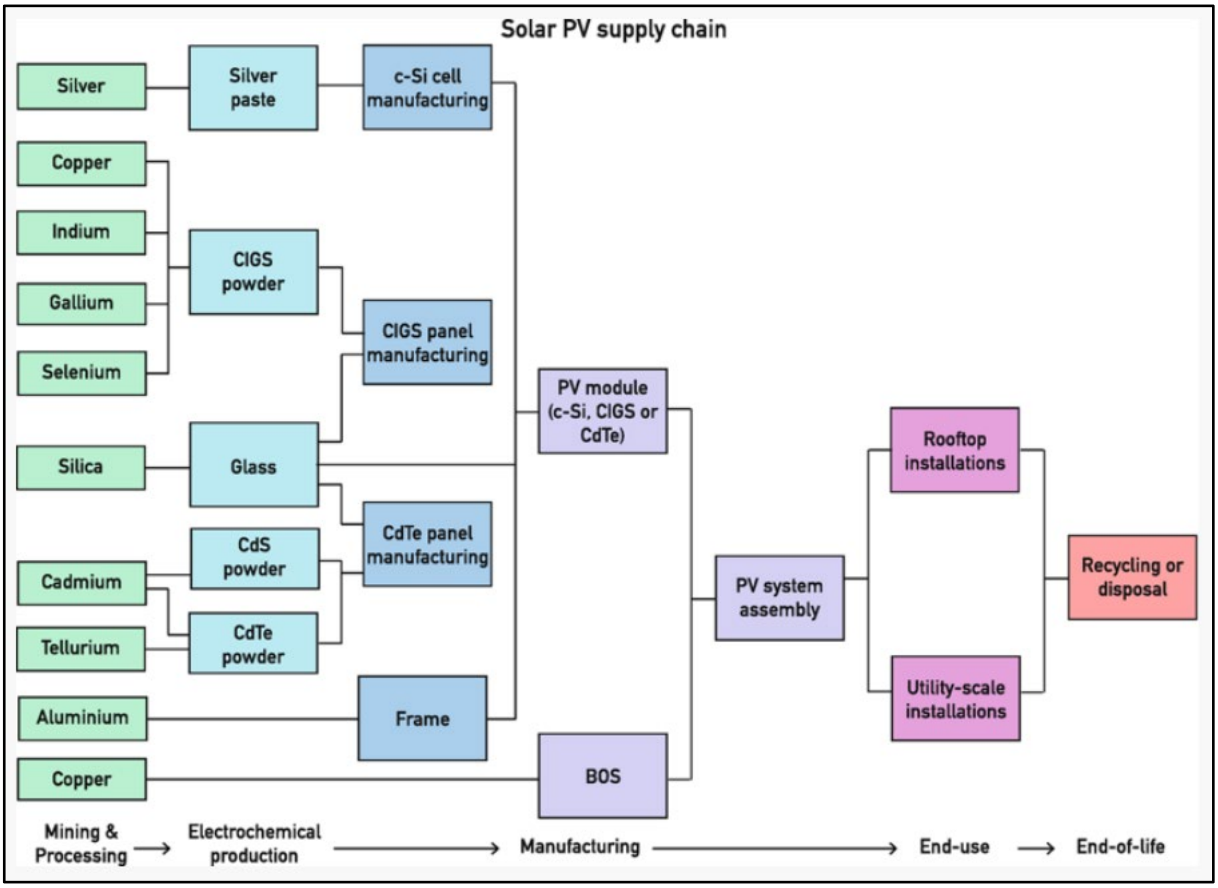



**Figure 3: Overview of solar PV panel supply chain**
(Giurco et al. 2019)

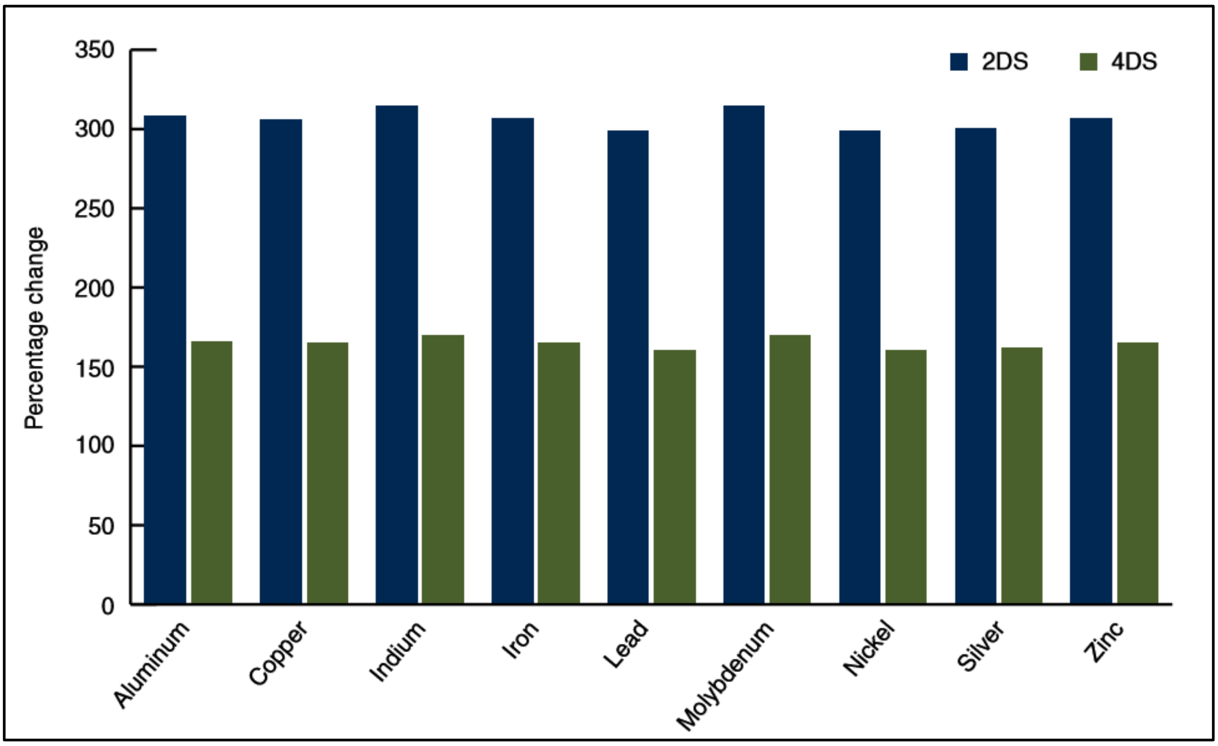



**Figure 4: Median metals demand scenario for supplying solar photovoltaics through 2050**
(World Bank 2017)

*2.3 Wind Energy*

The most prominent wind turbine technology is a horizontal-axis turbine, with three blades that rotate upwind around a horizontal axis on a tower, and steel components accounting for 80% of the total weight. Other materials include bulk commodities such as copper, aluminum, concrete, and carbon [18], [33]. Rare earth metals (neodymium and dysprosium) are used in direct-drive permanent magnet generators and can be found in roughly 20% of all installed turbines [34]. Direct-drive generators are often favored for offshore installations due to reduced maintenance needs and increased reliability, with the role of each material being illustrated in Figure 5 [35] .

With wind power already being one of the most established renewable technologies, requirements are not expected to change drastically. Off-shore technology does generally require a greater amount of materials, but concerns with supplies revolve around the increasing quantity of turbines using direct-drive permanent magnet generators (PMG). The Global Wind Energy Council's 2018 report shows that the current share of the total global offshore installations represents four percent of the total 591 GW installed [36]. By 2025, the share is expected to exceed 10 percent, and the total installed based could reach 100 GW [36]. With neodymium and dysprosium being among the materials with the highest supply risks, Dominish et. al (2019) suggest that installation types are likely linked to supply constraints, and that PMG's could be implemented in greater quantities if new rare earth mines and processing facilities are established [8], [18]. However, as of 2019, there is no commercial recycling of neodymium or dysprosium, despite promising research from the Critical Materials Institute (CMI) and the Ames Laboratory [37]. The lack of a secondary supply for these metals is crucial, as the World Bank outlines median metals demand for wind technology through 2050 to increase by ≈150% in a 4°climate scenario, and ≈250% in a 2°climate scenario [2]. The same evaluation found possible cumulative demand for neodymium to increase to over 350,000 tons, despite current total annual production currently only being around 7,000 tons (Figure 6) [2].

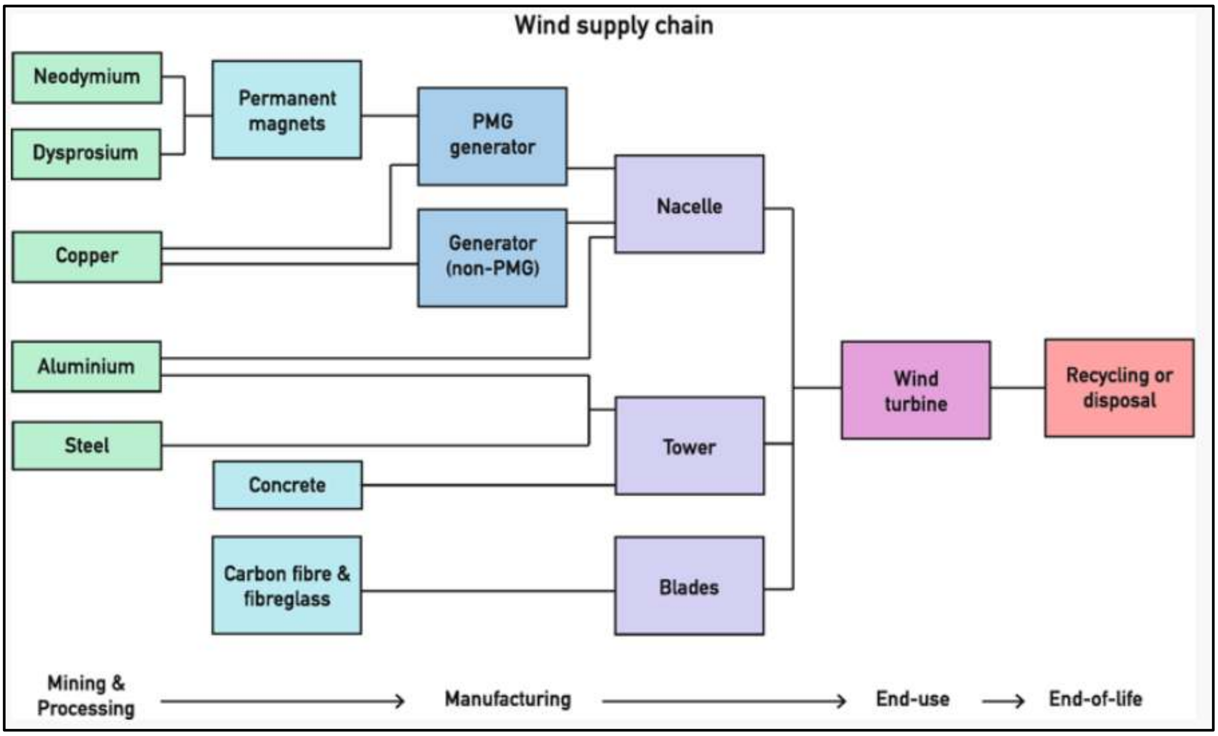
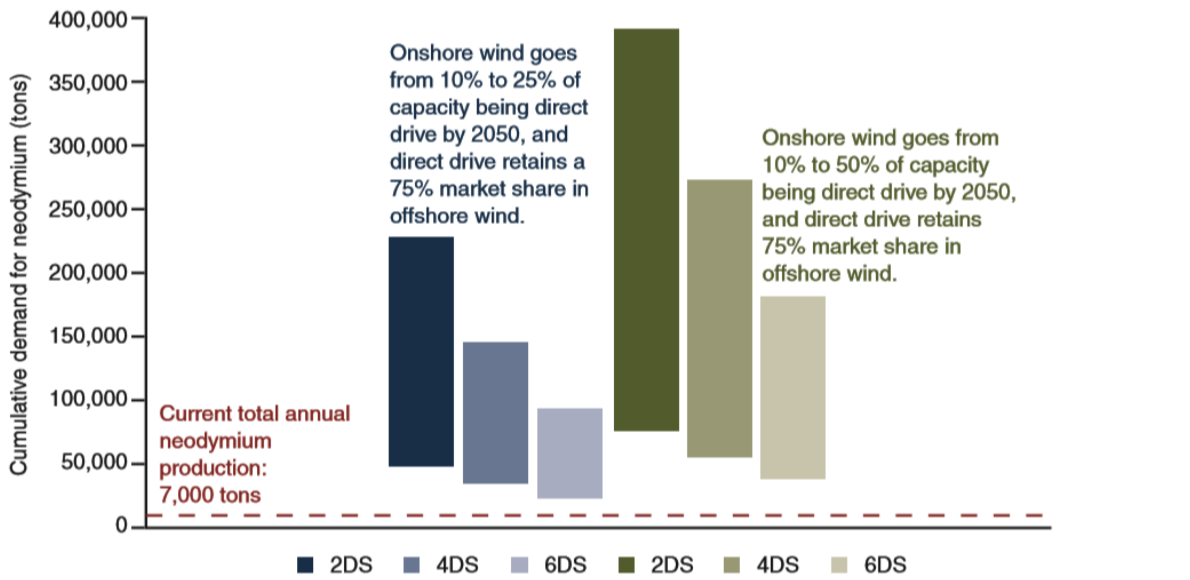



**Figure 5: Overview of wind turbine supply chain**
(Giurco et al. 2019)




*Note:* 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario. Each bar represents an energy scenario (2DS, 4DS, or 6DS) and set of assumptions about the market penetration of direct drive vs. geared wind turbine technologies. The height of the bar is the uncertainty in the intensity of metal demand (high versus low estimates of the amount of neodymium in each generator). In this figure, offshore wind turbines have a consistent 75/25 split for direct-drive and geared systems, respectively, from 2013 through 2050. In the blue scenarios, onshore wind turbines have a consistent 25/75 split for direct-drive and geared systems, respectively, from 2013 through 2050. In the green scenarios, direct-drive systems in onshore wind turbines move from a 25 percent market share in 2013 to a 50 percent market share in 2050.

**Figure 6: Ranges for cumulative neodymium demand for global wind turbine production through 2050**

(World Bank 2017)

*2.4 Other Technologies and Material Requirements*

Other renewable technologies that have been assessed based on their demand for critical materials are concentrated solar power, LED lights, power infrastructure, and fuel cells. The use of concentrated solar power (CSP) as a major global source of energy would lead to a large increase in demand for nitrate salts ($NaNO_3$ and $KNO_3$), silver, and steel alloys [38]. Among end use technologies, LED lights are preferred over incandescent light bulbs due to higher efficiency, but they require indium and other metals that are also used in thin film solar PVs [39]. The recent adoption of energy-efficient lighting technologies in general has led to increased demand for several critical raw materials including rare earths (Eu, Tb and Y), gallium, germanium and indium [39]. The next-generation of lighting technology, organic-LED (OLED), is expected to limit the need for critical materials, but wide adoption is not expected before 2025 [39]. Renewable energy transitions may also require materially intensive investments in power infrastructure, such as copper in HVDC-lines, and stationary grid storage with vanadium redox flow batteries [40]. Harmsen et al. (2013) estimate that deteriorating ore quality could lead to a gross energy requirement for copper production in 2050 that is 2–7 times higher than it is today [40]. Finally, the use of fuel cells for stationary storage and EVs requires the use of platinum, the price of which has historically been very sensitive to demand [41].

## 3. Material Supplies

This section examines the markets, reserves, and supplies of the minerals needed for clean energy technologies to determine whether they could constrain the energy transition. We focus in particular on minerals that are thought to be directly impacted by the energy transition, including lithium, cobalt, rare earth minerals, indium, tellurium, and silver.

Investigations into the material needs of the energy transition have left little doubt that a low-carbon economy will be more, rather than less, material intensive, but physical scarcity will most likely not be among possible limiting factors [2], [13], [18], [42]–[46]. Theoretical demands for various carbon mitigation objectives and assumed energy needs (e.g.,[10]–[14]) imply potential bottlenecks with drastic demand increases (Figure 7), but also highlight evolving opportunities provided by growing markets, reserves, and technological changes. This disconnect between mitigation and opportunity becomes especially tangible when examining reserves, resources, and supply across the world, as it is important to view materials in the context of their entire supply chain [2].

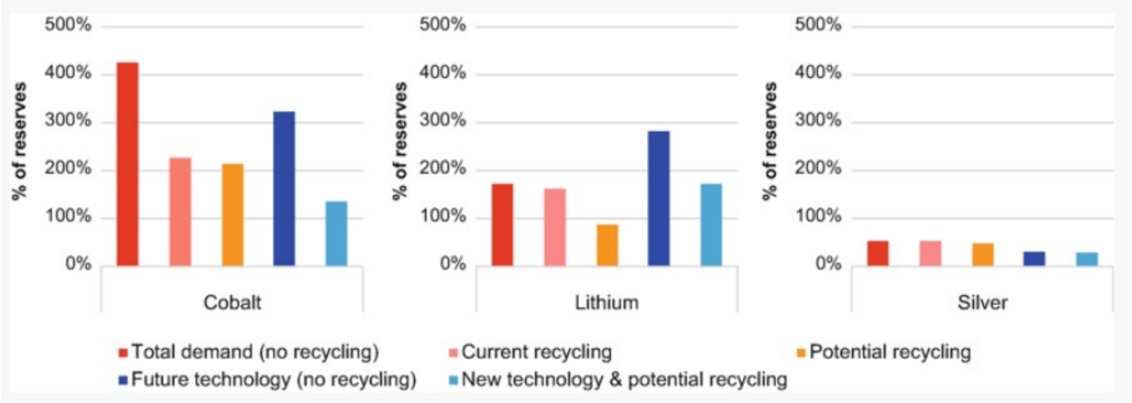



**Figure 7: Cumulative demand from renewable energy and transport technologies to 2050 compared with reserves** (Giurco et al. 2019)

*3.1 Lithium Supply*

Recent research indicates that the development of current lithium resources will allow for a sizeable market of electric vehicles (e.g., [12], [13], [47]–[50]), and will not act as a barrier to the energy transition [12], [13], [47]–[50]. Olivetti (2017), Gruber (2011), and Kushnir (2012), instead rightfully shift focus towards flow rate into society and supply security [10], [12], [13]. Three of the top five countries (Bolivia, China and Argentina) with the largest recoverable lithium stocks are associated with high forms of institutional risk, and are not producing as much as they are capable of [2]. This is exemplified by the U.S. Geological Survey's 2019 mineral commodities summary, which cites Chile as having roughly three times the lithium reserves of Australia, despite Australia producing 51,000 tons to Chile's 16,000 tons [9]. Similarly, Argentina's 14.8 million tons of resources and 2,000,000 tons of reserves only produced 6200 tons of the 85,000 tons of lithium extracted in 2018 [9].

Partially due its aggressive stance on foreign involvement, Bolivia has yet to even develop its resources despite supposedly hosting 9 million tons of lithium resources [2], [9], [51]. In addition to these institutional problems, Bolivia's lithium resources require more input than their neighbors' as a result of their lower quality brines (higher magnesium contamination), and higher precipitation [52]. These changes cause the evaporation process to be more costly in addition to compounding logistical constraints [52]. Aware of potential supply changes, and as the world's largest global lithium consumer, China has recently (2019) invested in a $2.3 billion lithium project in Bolivia as a joint venture with the Bolivian state owned company YLB [53]. Enormous investments like these, that are somewhat independent of economics, and Bolivia's recent claims that the lithium rich salt flats now hold " more than double a previous estimate" (Ramos 2019), make it difficult to analyze potential constraints from a resource perspective

*3.2 Cobalt Supply*

With high supply risks, cobalt is often at the forefront of discussions regarding sustainable development, but supply concerns might be overstated [8], [54]. While it is possible for demand to outpace reserves, policy decisions and technical changes will also shape the availability and need for cobalt. Månberger & Stenqvist (2018) concede that changing battery technology has the ability to reduce future cobalt needs, while Guirco et. al. (2019) warns that their energy scenario is "ambitious", with a 100% renewable transport system by 2050.

Calls for increased transparency are putting pressure on EV companies to source cobalt sustainably. Fortune's crisis report, *Blood, Sweat, and Batteries*, and other investigations into child mining in the Democratic Republic of Congo, have electric vehicle manufacturers announcing that they are looking for cobalt alternatives [20], [23],[55], [56]. Other supply concerns stem from the DRC's history of instability and China's control cobalt refinement [9], [57], [58]. With over 65% of the world's cobalt coming from the DRC, there is a strong reliance on the nation's ability to produce [59]. The DRC's 3,400,000 tons of reserves are the largest in the world, but the U.S. Geological Survey also puts global terrestrial cobalt resources at 25 million tons [9]. These concerns, among other factors, have caused price volatility for the metal, with prices dropping as much as 40% in the span of a few months [60]. As such, government incentives, technical changes, recycling, and alternative sources can all be used to offset potential shortages in the near future if necessary.

### *3.3 Rare earth elements (REEs)*

The availability of rare earth elements (often-abbreviated REEs) is more nuanced than reserves and resources. The U.S. Geological Survey describes rare earth elements and metals as being relatively abundant in the Earth's crust, although mineable/processable concentrations are limited and more nuanced [9], [61]. Yet, despite commonality, China was responsible for 70% of mine production in 2018, without accounting for illegal artisanal mining in the region [9]. Demand needs are further complicated by rare earths occurring with radioactive elements such as thorium. Joint production of rare earths also makes supply of each, and their relative prices, sensitive to changes in demand for the others. This secondary nature, with the exception of China's clays and carbonatites, hinder the ability to accommodate rapid increases in demand, and makes the separation process environmentally burdensome. This difficulty in separating REE concentrates into usable elements allows for China to control 90% of the world's refinement and processing capabilities along with90% of the world's supply [62], [63]. However, China's dominance of the market, and the precedent set by the 2010 rare earth trade dispute, have caused an increase in investment for rare earth projects outside of China. Although not at working capacity yet, partially owned by China, and not able to process REEs, the U.S. reopened its only rare earth mine in California in 2018 [63]. There are also at least three U.S.-based companies with rare earth processing plants under construction or in the planning stages [63]. Australia is also implementing development deals to strengthen its production while trying to counter China's dominance of the market [64], [65]. Further complications involving trade wars between the U.S. and China have raised questions regarding reliance on China for rare earth materials in the future, and what can be done to mitigate dependence [62], [66], [67]. Other developments including rare-earth recycling, the "tremendous potential of deep-sea mud as a source of rare-earth elements"(Takaya et al. 2018), and the U.S. Department of Energy's multi-million dollar investments into recovering rare earth elements from combusted coal, illustrate a complexity that goes beyond direct supply shortages.

### *3.4 Indium, Tellurium and Silver*

More than other technologies, the solar panel industry is often labeled as the most likely to be affected by material shortages [7], [14], [25], [32], [42]. Production concerns regarding indium and tellurium (for use in CIGS/CdTe) and silver have been specifically discussed, with claims that demand through 2050 may exceed current reserves (but not resources) for all three materials [14]. One of the key problems is that indium and tellurium are both secondary metals whose supply depends on growing demand for more common companion metals [68]. The World Bank's 2017 report and calls for resource governance to map minerals in developing nations, raise concerns on how reliable the data on these commodities are [2], [69]. As Indium was not recorded as being recovered at all in the United States for 2018, and quantitative estimates of reserves are not available for any country (although resources are), it is hard to judge its viability to respond to demand [9]. Therefore, flow rates are more important than reserves for secondary metals. Frenzel et al. (2017) go so far as to claim that indium production could increase by 300% without increasing zinc production, but the feasibility and economic viability of this increase has not been thoroughly assessed [70]. In the case of tellurium, the possibility of recovery from copper production, and the market dominance of c-Si panels (no tellurium necessary), may also limit demand concerns [25]. Rising commodity prices, large scale mining implementation, or adaptation by copper producers, might be able to mitigate shortages for numerous critical materials relating to PV technologies [9], [14]. Solar PV technologies also currently consume approximately 7% of end-use silver, and demand projections show panel requirements overtaking 70% of known reserves by 2050, although gold and silver mines account for a large portion of exploration projects [14], [32]. Further exploration of resources, end of life management, technical innovations, social constraints, environmental considerations, and general policy changes are most likely to determine the extent of solar PV material shortages [25].

## 4. Investment Strategies

This section examines and compares national investment strategies regarding materials necessary for the energy transition.

The nature of investments into the extraction and refinement of minerals will shape the speed and efficiency of the energy transition. The World Bank's 2017 report on the growing role of minerals and Bloomberg New Energy Finance's outlook on emerging markets both contend that "developing nations are today leading a global clean power transition" (BloombergNEF, 2018), with non-renewable mineral resources dominating energy production in 81 countries [2], [71]. This outlook reflects the trend of developing countries advancing their material resources, but does not adequately consider the volatile role that larger economies will play in their development. The United States' "commitment" to material security, China's aggressive commercial diplomacy through the One Belt One Road initiative, and the possibility of material shortages all create unique investment challenges and opportunities across the world [62], [72]–[75].

### *4.1 Chinese Investment*

Investigations into renewable energy investments in China revolve around the Belt and Road Initiative (BRI), China's commitment to asset financing, and general control over mineral processing [63], [74], [76]. China's clean energy policies and investment strategies mean that they have committed $758 billion between 2010 and the first half of 2019, with the U.S. a distant second at $356 billion [77]. However, as both the largest investor in renewable energy and the world's largest polluter, China has been essential in the build-out of both solar and coal, adding more than 200 GW of each during the 2010s [77]. Independent scientific analysis by Climate Action Tracker shows that China is on track to meet its 2030 Nationally Determined Contribution (NDC) and will likely achieve its 2020 pledge, but its actions are rated "Highly insufficient" and detrimental to carbon mitigation goals [78]. However, as the leader in renewable trends and investments, China's commitment to securing material supply chains necessary for the energy transition, and its actions through the BRI, ensure that it will remain the leader in the changing energy sector. Policy briefings created by the Strategic Dialogue on Sustainable Raw Materials for Europe (STRADE) conclude that mining asset acquisition is not central to the One Belt One Road initiative, and that "China is no longer 'the dragon' that is seeking to purchase global mineral assets" [79]. The Council on Foreign Relations instead describes China's goals as being to foster general economic growth through the expansion of markets while creating a more assertive and essential China [73]. What is not discussed in many of these perspectives is that this framework of outward involvement, with infrastructure at its core, positions China to strengthen its hold on the materials necessary for the energy transition.

*4.1.1 The Belt and Road Initiative*

A less exclusive continuation of China's "Go Out[2]" international investment policy, the BRI is driven by China's state owned enterprises (SOEs). STRADE's 2018 European Policy Briefing reported that among the 50 most influential enterprises participating in the BRI, 42% are private enterprises, 56% are a type of SOE, and 2% are joint venture enterprises [79]. In the past, this use of state backed investments allowed for China to gain control of large portions of cobalt, platinum-group metals, and lithium reserves, as other nations struggled to incentivize multinational investment [80]. FP Analytics' 2019 report *Mining the Future* accurately discusses the lasting implications of this approach, and how China is "set to dominate the next industrial revolution", but does not explore the effects of the BRI initiative. This is possibly because, as STRADE points out, the BRI deals have no overarching structure, no membership protocols, no moralistic brow beatings, and no predefined set of standards [79]. Each country or bloc negotiates on their own terms, and deals can be structured in accordance with each set of particular parameters or development goals [81].

Combined with a general lack of transparency through Chinese policy, there have not been adequate investigations into the development of the BRI and the materials of the energy transition [82]. STRADE's European Policy brief went so far as to say that "declining interest in overseas metals and mining investment, particularly under the BRI can simply be a result of the lack of accurate data on Chinese investments" [79]. However, looking at infrastructure development projects in the past, especially in Africa, influences on supply should definitely be considered. The China Africa Research Initiative's 2016 report on Chinese loans in Africa tried to dispel ideas that China has been solidifying its control over materials through loans to developing nations [82]. Yet, as Foreign Policy Analytics' report discussed, China's infrastructure investment in the DRC turned into ownership of 10 out of the DRC's 18 major operational mines, six major development projects, a three-year off-take deal from the world's largest cobalt mine, and influence over 52% of the country's supply [80]. Furthermore, Bloomberg NEF's report on emerging markets and the Council on Foreign Relations warn of potential debt traps, and that investments from the BRI can be considered a poisoned chalice [71], [83]. This is especially important when considering that CARI estimates 33% percent of Chinese loan finance in Africa is secured by commodities or exports of natural resources [71], [83]–[85]. The general level of investment in resource rich nations is shown in Figure 8 [84].

[2] Go Out policy is the People's Republic of China's strategy to encourage its enterprises to invest overseas.

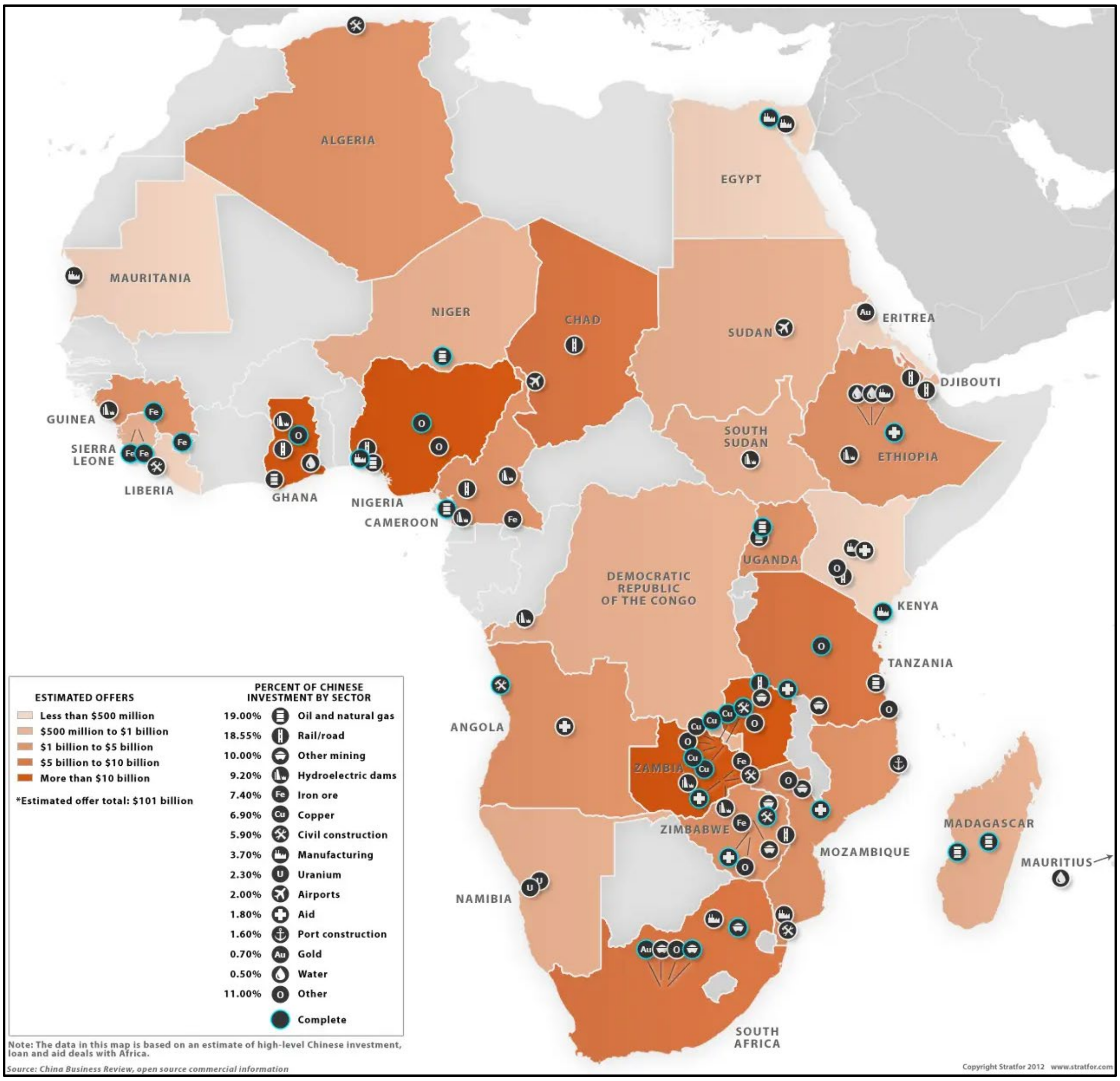



**Figure 8: Chinese Investment Offers In Africa Since 2010**

(Stratfor 2012)[84]

*4.1.2 Refinement in China*

Beyond infrastructure development, China is adapting to the needs of market-oriented countries and solidify its role in the processing of critical materials. With control of international resources becoming increasingly difficult, trade and refinement agreements ensure that market control can be maintained. China’s $4.1 billion purchase of a 23.77 percent stake in Sociedad Química y Minera, a Chilean chemical and mining company, and China's Tianqi Lithium, which holds a 51% stake in Australia's Greenbushes lithium mine, ensures that they control over half the world's lithium production [85]–[87]. China’s more recent 49% stake in a $2.3 Billion planned venture with Bolivia’s state lithium company, YLB, will only increase lithium imports and refinement, especially if claims that Bolivia’s resources are the largest in the world prove true [53]. With high import control, China’s Tianqi Lithium and Ganfeng Lithium are among the largest lithium and lithium compound producers in the world, and help China to maintain its status as the world's largest producer of lithium batteries [19], [88]. This will likely continue, as Chinese government backed organizations can continue to make strategic long-term investments whereas privately owned corporations in the rest of the world maintain concerns about price volatility and returns.

The European Union's *Study on the Review of the List of Critical Raw Materials* (Table 1) shows that China is the major global supplier of 30 out of the 43 individual critical raw materials (as defined by the EU), despite a large majority of the materials being mined in other locations [8]. China's ability to serve as a refinement crux is perhaps best expressed through their control of rare earth elements and cobalt. China is currently the largest importer of raw cobalt, accounting for 40% of global trade value, and is the world's leading producer of refined cobalt, the leading supplier of cobalt imports to the United States, and the leading consumer of cobalt [10]. Similarly, despite the opening of the rare earth mine in Mountain Pass, California (partially owned by China), the United States is reliant on China for 100 percent of its rare earth supply due to processing constraints [63], [89]. Furthermore, with China already being the destination of 15 to 16 percent of sub-Saharan Africa's exports, and the source of 14 to 21 percent of the region's imports before the Belt and Road Initiative, it will likely maintain its control over a large portion of numerous material markets [83]. This control, and use of large scale vertical integration, allows for it to be the largest seller of electric vehicles, the largest producer of wind turbines, and home to the three largest solar module suppliers [76], [83], [90]–[92].

| Material | | Stage[13] | Main global supplier | Share | Material | | Stage | Main global supplier | Share |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Antimony | P | China | 87% | 23 | Natural graphite | E | China | 69% |
| 2 | Baryte | E | China | 44% | 24 | Natural Rubber | E | Thailand | 32% |
| 3 | Beryllium | E | USA | 90% | 25 | *Neodymium* | E | China | 95% |
| 4 | Bismuth | P | China | 82% | 26 | Niobium | P | Brazil | 90% |
| 5 | Borate | E | Turkey | 38% | 27 | *Palladium* | P | Russia | 46% |
| 6 | *Cerium* | E | China | 95% | 28 | Phosphate rock | E | China | 44% |
| 7 | Cobalt | E | DRC | 64% | 29 | Phosphorus | P | China | 58% |
| 8 | *Dysprosium* | E | China | 95% | 30 | *Platinum* | P | S. Africa | 70% |
| 9 | *Erbium* | E | China | 95% | 31 | *Praseodymium* | E | China | 95% |
| 10 | *Europium* | E | China | 95% | 32 | *Rhodium* | P | S. Africa | 83% |
| 11 | Fluorspar | E | China | 64% | 33 | *Ruthenium* | P | S. Africa | 93% |
| 12 | *Gadolinium* | E | China | 95% | 34 | *Samarium* | E | China | 95% |
| 13 | Gallium* | P | China | 73% | 35 | Scandium | P | China | 66% |
| 14 | Germanium | P | China | 67% | 36 | Silicon metal | P | China | 61% |
| 15 | Hafnium | P | France | 43% | 37 | Tantalum | E | Rwanda | 31% |
| 16 | Helium | P | USA | 73% | 38 | *Terbium* | E | China | 95% |
| 17 | *Holmium* | E | China | 95% | 39 | *Thulium* | E | China | 95% |
| 18 | Indium | P | China | 56% | 40 | Tungsten | E | China | 84% |
| 19 | *Iridium* | P | S. Africa | 85% | 41 | Vanadium | P | China | 53% |
| 20 | *Lanthanum* | E | China | 95% | 42 | *Ytterbium* | E | China | 95% |
| 21 | *Lutetium* | E | China | 95% | 43 | *Yttrium* | E | China | 95% |
| 22 | Magnesium | P | China | 87% | | | | | |

| Legend | |
|---|---|
| Stage | E = Extraction stage P = Processing stage |
| HREEs | Dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium |
| LREEs | Cerium, lanthanum, neodymium, praseodymium and samarium |
| PGMs | Iridium, palladium, platinum, rhodium, ruthenium |

*Global supply calculation based on production capacity.

**Figure 9: Global supply of Critical Raw Materials**

The 15 rare earth elements (REE) are split into two sub-categories based on their chemical and physical properties – 'heavy' rare earth elements (HREE) , consisting of ten individual materials, and 'light' rare earth elements (LREE), comprising five individual materials. The five platinum group metals (excluding osmium) (PGMs) are also grouped. (European Commission 2017)[8]

### *4.2 United States Investment*

This section examines US investment strategies of the United States through its role as the world's largest economy and as a contrast to Chinese strategies.

#### *4.2.1 Substitutions*

Investments in material supply chains for the United States have primarily focused on technical advancements and have yet to reach the level of involvement required to maximize their benefit from the energy transition. The United States began to develop their critical material strategy in 2010 directly focusing on emerging clean energy technologies following China's REE export dispute in the same year [93]. The Critical Materials Strategy expressed a need to "facilitate extraction, processing and manufacturing here in the United States", and even discussed future demand projections for renewable energy technologies [93]. The impact of the initiative is unclear, and after 2011 the Department of Energy awarded $120 million to the Critical Materials Institute (CMI) to "assure supply chains of materials critical to clean energy technologies" [94]. The CMI has made advancements in critical material substitutions, but as their orientation is purely technical in nature, they have not actively incentivized investment or the exploration of resources like China has [95]. In the following years, the United States government invested heavily in the recovery of REE from coal and coal byproducts [96]. Recent advancements have prompted a further investment of $20 million for "Process Scale-Up and Optimization/Efficiency Improvements" for the Department of Energy-National Energy Technology Laboratory Rare Earth Element Program in April of 2019 [96]. The impact of these substitutes will likely prove substantial in future supply concerns, as Sprecher et. al's 2017 study on critical materials showed the positive impact of substitutes for rare earth materials (Figure 10) [97].

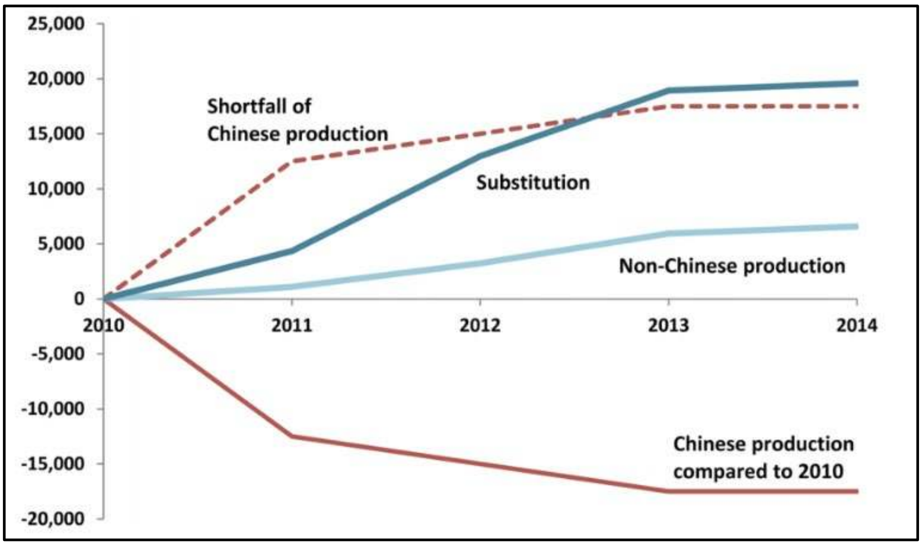



**Figure 10: Rare Earth production following 2010 Chinese export restrictions**
(Sprecher et al. 2017)[97]

*4.2.2 Goals for Mineral Independence*

Following an executive order in 2018, the United States created the *Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* with the intention of progressing toward mineral independence [72]. With a call to action, this strategy solidifies objectives put forth in the United States' first critical materials strategy, with the additional goals of aiding in the cataloging of possible resources, permitting and leasing on federal land, and the growing of the relative American workforce [72]. Although this appears to address a few investment concerns, particularly regarding necessary workforces, it does not present many actionable objectives regarding supply chains. The strategy's narrative is broad in scope and, beyond stating policy, it is unclear what monetary incentives or actions it contributes to accomplish its goals. This disconnect between the strategy and implementation, or supply and investment, is a major gap in the United States' goal to limit its heavy import reliance (Figure 11).

Since it may take a decade or more to open a mine, the United States' lack of investments in new mining operations can create problems if faced with increases in production or rapid commitment to renewable energy [45]. The 2017 U.S. Geological Survey's Exploration Review shows a "recovery for mineral exploration" and investment in 2017, but also warns of United States' mining companies shifting focus towards projects with short-term development [98]. The report also warns of a 13% decline in exploration companies headquartered in Australia, Canada, and the United States, and only 20% of active exploration sites having mineral targets other than gold, silver, and base metals [98]. Investment in California's Mountain Pass mine, the United States' sole rare earth mine, is often praised despite it only being pulled out of bankruptcy in 2017. The site also has an idle $300,000,000 building that the company calls the "crack house" from its previous mismanagement [99]. MP Mine Operations LLC, the owner of the mine (along with Chinese partner Leshan Shenghe Rare Earth Co.), say they are "literally going around shutting off lights" due to the tariff on rare-earth ore shipments to China, resulting from the Trump administration's own tariffs [89]. Plans to open rare earth processing plants in the United States are progressing, with the first set to open in 2020, but other efforts are still in the early stages and would likely only process locally extracted rare earth compounds [63], [64]. The 2019 USGS commodity summary on rare earths shows that the United States' mine production was only 15,000 tons of the 170,000 produced globally, all of which was processed in China [9]. As such, in 2018 the United States had a 100% net import reliance and imported an estimated $160 million worth of rare-earth compounds and metals; an increase from $137 million in 2017 [9].

According to Bloomberg NEF's emerging markets outlook, administrative actions in the United States have lead to instability concerns and broader difficulties for investment in emerging markets [71]. Although these actions could lead to greater investment in the United States' own mining industry, administrative actions have shown that supporting these types of investment are not a priority for the current administration, especially in regards to preparing for a low-carbon economy. Combined with uncertainty about the effects of federal tax reform legislation and new import tariffs, there is a great deal of uncertainty surrounding general investments in materials and technologies necessary for low-carbon energy. Because of this, relevant investments are primarily driven by actions at the state and private level. Deloitte's Renewable Energy Industry Outlook for 2019 cites that over the past two decades, nearly 50 percent of U.S. wind and solar development was driven by state mandates, especially renewable portfolio standards, and that many corporations headquartered in the United States have committed to achieving 100 percent renewable power as part of the RE100 campaign [100].

Investment into clean energy development in the United States rose 12% to $64.2 billion in 2018 due to state involvement, but the lack of clear federal policy and federal investment into mapping mineral resources is likely to create problems in the future. Insights by Sykes et al. (2016) on transformational change in the critical materials market warns that the recognition of future potential demand will not be enough to incentivize growth [101]. The economic history of mining and metal markets show that a combination of breakthroughs in discovery, supply, and demand factors will all be required for transformative growth [101]. Similarly, Koning et al. (2018) warns that major issues with demand-supply imbalances and price hikes will occur if policies are unexpectedly and widely adopted, causing a much faster transition to low-carbon technologies and electric vehicles [45]. This scenario is becoming increasingly likely, as the transition to renewable energy will occur in spite of the U.S. government's commitment to coal and scrubbing of climate change data from federal websites [102]. This level of passive investment creates uncertainty and volatility due to the United States being one of the world's largest economies, and one of the nations most confused about its own climate policy.

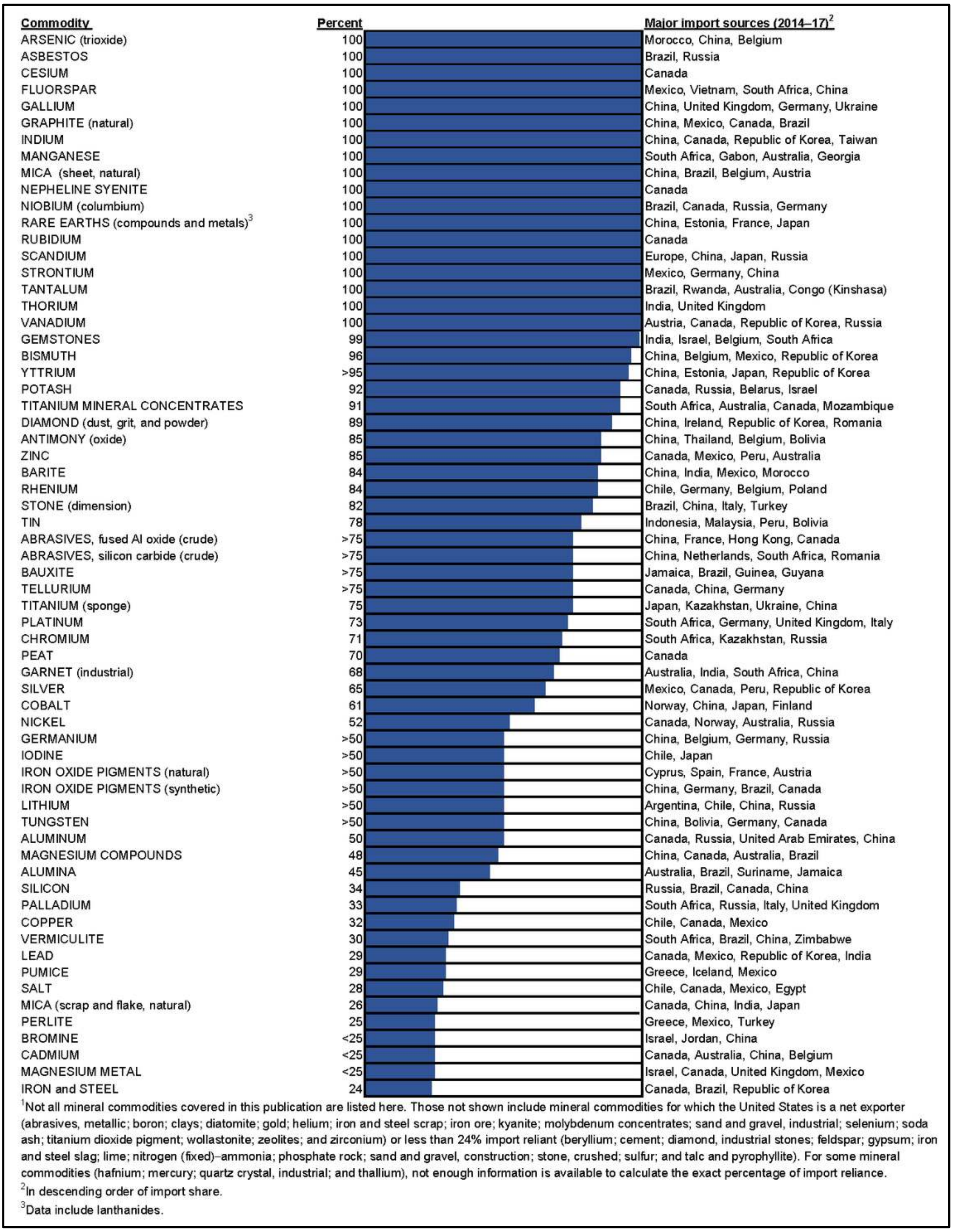



**Figure 11: 2018 U.S. Net Import Reliance**

(U.S. Geological Survey, 2019)[9]

## 5. Environment, Governance, Society, and Artisanal Mining

In this section, the impact of environmental and climate concerns, governance, and artisanal mining are examined in the context of material supply considerations.

As mineral resources begin to play a larger role in the energy transition, it is important to examine the role that local communities will have on improving the sustainability of mining practices and the reliability of supply. As described in the World Bank's 2017 overview of extractive industries, nonrenewable mineral resources play a dominant role in 81 countries that collectively account for a quarter of world GDP, half of the world's population, and nearly 70 percent of those in extreme poverty [103]. The 2017 Resource Governance Index (RGI) and the Natural Resource Governance Institute (NRGI) found that of countries monitored, 42 percent of mineral reserves are in countries with "good" or "satisfactory" governance scores, 37 percent are in countries with "weak" scores, and a further 7 percent are in countries that score "poor" [104]. The International Institute for Sustainable Development (IISD) maintains that the way materials are sourced will determine whether the energy transition supports peaceful, sustainable development, or exacerbate local tensions and grievances [3]. The implications of this can be seen in Figure 12, where many of the resource rich areas such as North-Eastern Africa, and parts of South America, are rated as relatively fragile or corrupt. States with high scores were rated worse on 12 different indicators including human rights, public services, demographic pressures, refugees and internally displaced persons, and security. The effects of these relationships are sometimes discussed in the context of investment risks, such as in reports put out by Bloomberg NEF, but the scope of their potential influence has not been well defined outside of the mining industry [71]. With increasing demand, mining projects in developing countries have become more commercially attractive, and this new interest can lead to potential issues with supply disruption through environmental damage, corruption, and local conflicts.

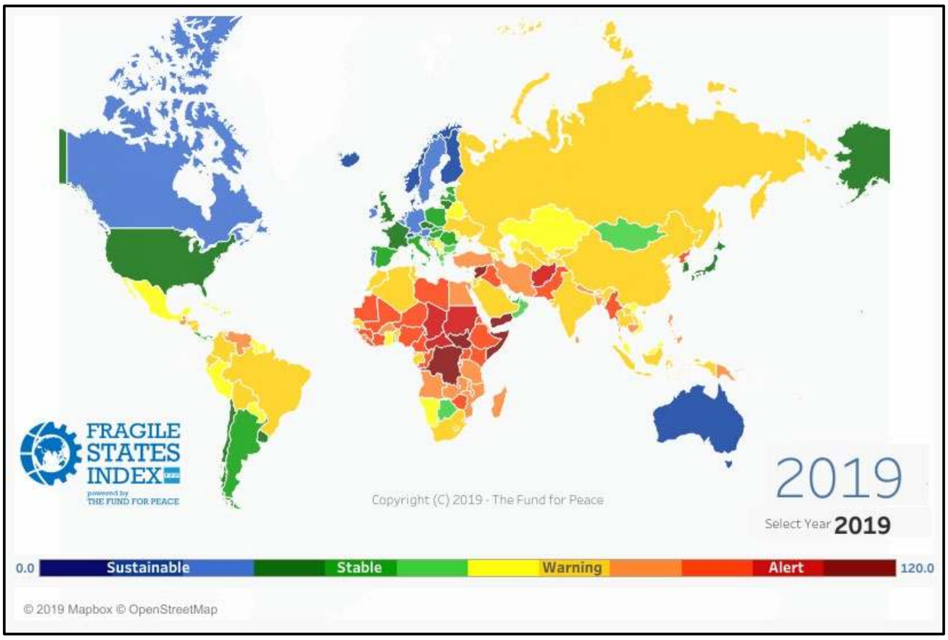



Figure 12: Fragile States Index
(Fragile States Index.)[105]

*5.1 Environmental Concerns*

Environmental concerns and questions about the climate footprint of the materials necessary for the energy transition are only beginning to be properly discussed by policymakers despite environmental health being a large motivator for the transition. It is important to look at the full lifecycle of clean energy technologies and their materials to ensure that they make net positive contributions to the fight against climate change. Pollutants (tailings, emissions, and other physical wastes) from extraction and processing account for half the world's worst ranked industries and are responsible for many of the most toxic locations on Earth [106]. Non-profit PureEarth (formerly the Blacksmith Institute) reports that 92% of pollution related deaths occur in low and middle income countries [107]. While these deaths are sometimes the result of uncommon, negligent mining practices, the Natural Resource Governance Institute is warning that accountability may start to be outweighed by potential material profits in nations with poor governance scores [104]. The implications of this lack of accountability can be seen in Zhiyuan Li's 2014 investigation of heavy metal pollution in areas surrounding Chinese mines [108]. The investigation gives detailed descriptions about the overall pollution levels and health risks posed by heavy metals in the soils of various mining areas throughout China, which are only expected to get worse [108]. Similarly, the parts of Zambia and the DRC that host the Central African Copperbelt are considered one of the top ten most polluted areas in the world as a result of the discharge of pollutants from mines and smelters [109]. A general lack of accountability in this area has led to heavy metal contamination of air, water, soil and plants with heavy metals and lasting health impacts [18], [108]. Along with health issues for miners and surrounding communities, these changes can lead to conflict with local populations. Another example of this is Australian based company Lynas Corp., one of the only REE suppliers in the world, which lost half of its stock value during 2018-2019 after concerns arose regarding low-level radioactive waste generated by its refinement plant in Malaysia [110].

Research on greenhouse gas emission disclosure from the minerals sector also highlights the scale of climate impacts from mineral companies and their supply chains, and how difficult supply chain emissions in particular are to capture [111]. Even among semi-responsible international entities, the ability to consistently trace emissions along the supply chain remains largely out of reach, making it challenging to set and track climate goals and develop procurement strategies for low-carbon minerals. With low global accountability, and an increase in scale with global supply chains, carbon emissions have the potential to become much worse in the coming years and need to be better understood to reach carbon goals.

*5.2 Conflict Minerals and Human Rights Abuses*

Regional conflicts and human rights abuses stemming from mineral extraction/markets are not new, but are also not often envisioned by policymakers as possible consequences of the low-carbon future. The International Institute for Sustainable Development's (IISD) 2018 report *Green Conflict Minerals* provides an overview of what minerals are at risk of becoming "fuels" for conflict in the upcoming transition, and lays a foundation for how dissemination of information and sourcing transparency can mitigate risks and conflicts [3]. However, while IISD's strategy involves supporting and engaging local communities in meaningful ways, many mitigation efforts rely heavily on civil society groups, the private sector, and governments acting as "watchdogs" who only try to limit involvement in these troubled areas [3]. This off-limits sourcing approach is based on incomplete understandings of root causes and often preempts a de facto boycott of all minerals even where there is no conflict at the time. Autesserre (2012) explores the consequences of off-limits, narrative driven intervention by showing that while simple cause & effect stories are necessary for policy makers, journalists, and advocacy groups, they create limitations and have a number of "perverse effects" [112]. In focusing overwhelmingly on technical responses and acting only through legislation and materials markets, other causes, consequences, and comprehensive solutions are often ignored [112].

Independent investigations into the 2010 Dodd-Frank act, which was intended to reduce the use of conflict fueling minerals, have found "conflict-free" legislation can sometimes be unintentionally detrimental to many of the mining communities they are trying to protect [55], [57], [113]–[115]. Due to concentrated narratives on how armed groups were able to fund their activities, the Dodd-Frank act was designed to reduce the use of specific conflict fueling minerals (conflict minerals) [116]. Specifically targeting resources from the DRC (tin, tantalum, tungsten, and gold), the legislation inadvertently created a de facto ban on artisanal mining that deprived hundreds of thousands of Congolese of their livelihoods [55], [57], [113]–[115], [117]. Furthermore, an investigation by Stoop et al. (2018) concluded that the legislation actually caused an increase in violence, in both the short and long term, since armed groups compensated their income losses by roving the countryside and increasing battles over gold mines [117]. As a result, an open letter was written and signed by over 70 Congolese and international academic observers arguing that the campaign fundamentally misunderstood the relationship between minerals and conflict in the eastern DRC [113].

While the results of Dodd-Frank are not representative of all conflict minerals initiatives or sustainable supply chain commitments, there is a disconnect between many renewable energy industries and the understanding of their impacts. Industry experts interviewed for the ISF's report *Responsible Minerals Sourcing for Renewable Energy* plainly stated that "reducing the environmental and social impacts of supply is not a major focus of the renewable energy industry" [18]. Amnesty International's 2016 investigation into corporate action and cobalt supply chains reported that all 26 companies failed to conduct human rights due diligence in line with international standards [118]. The 2017 repeal of a U.S. SEC rule requiring mining companies to disclose payments made to governments for access to natural resources, and a general history of human rights abuses from Chinese mining companies, show a continuation of the "material first" attitude of market economies [119], [120]. As Sovacool (2019) points out, improving the political economy of minerals in developing nations is a multidimensional and multi-institutional process that underscores the necessity of a diffuse chain of actors—including governments, technology firms, and consumers—accepting their own responsibility in the plight of the people involved [121]. Once corporations become more than passively involved in impacts they are having on material exporting nations, and consumers become fully aware of what their choices entail, then policy can be enacted that is perhaps both broader, but also more effective.

### *5.3 Artisanal Miners and Local Communities*

The role of local communities and artisanal miners is evolving into an essential part of resource management. Artisanal or small-scale mining (ASM) is often viewed as a subset or side effect of larger mining operations, but in actuality it is an essential part of life for millions of people in developing nations. In 2009, an estimated 5–20% of the African population directly depended on ASM, with more recent estimates shown in Figure 13 [122]. In 2013, The World Bank reported that 100 million people were directly engaged in artisanal and small-scale mining (ASM) compared to the 7 million people working in industrial mining in 2013 [122], [123]. With such high employment rates, ASM is believed to account for 15 to 20% of global non-fuel mineral production, and was estimated at one point to add 40% to official Chinese production of the REE [122], [124]. By having such a large impact on local communities and mining industries, the benefits of formalizing ASM go beyond integration and should be viewed as an essential part of mitigating supply chain instability and environmental concerns. In working with ASM communities, independent mining operations can operate within safe and effective supply chains and stop many of the negative environmental impacts associated with the toxic, low-cost practices often resorted to by ASM communities.

The World Bank's 2007 collaborative report on artisanal mining in the DRC documented how mining and mineral extraction can involve multiple pollution sources and pathways. In the DRC in particular, the Work Bank noted how mining and mineral extraction can pollute through drainage at mining sites, direct dumping of mine waste, sediment runoff, pollution from mining dredging in river beds, mercury pollution, chemical spills, sewage flows, and air emissions. Ditsele and Awuah-Offei (2012) also shows that large-scale operations tend to have lower life cycle environmental impacts than smaller operation, and because of the informal nature of ASM, governments do not often know of the existence of operations and cannot regulate them properly [125].

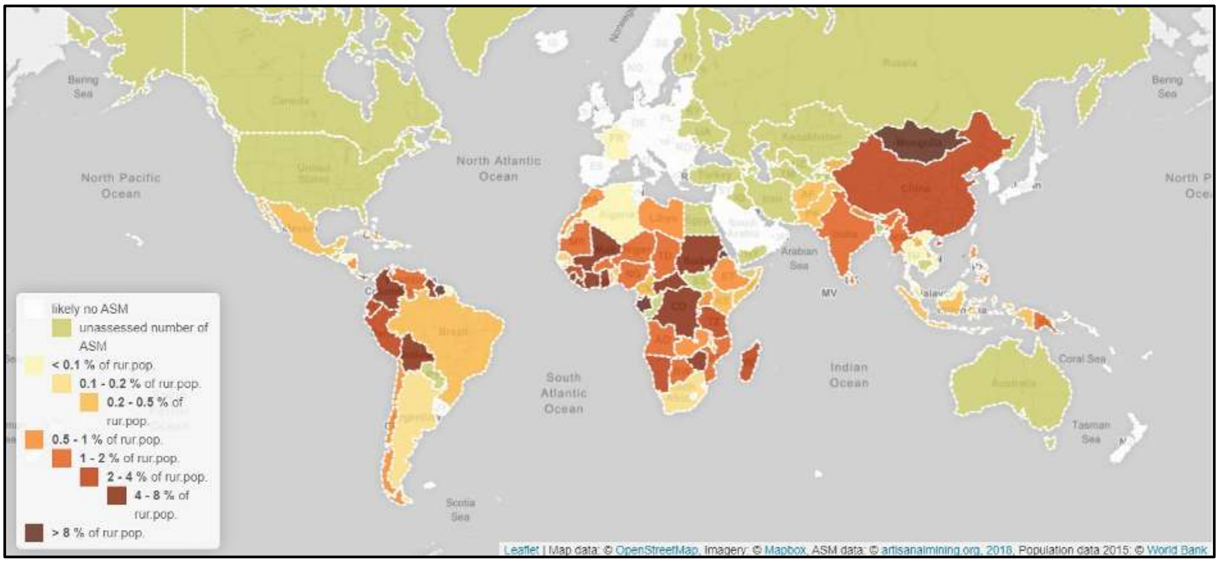



**Figure 13: Estimated number of artisanal and small-scale miners as percentage of rural population** (artisanalmining.org )[126]

*5.4 Social Concerns*

Mineral extraction does not only present environmental and regional governance concerns, it can also result in social issues such as exploitation, gender inequality, and child labor. For example, Marysse and Geenen (2009) report that Congolese trade agreements with China enable Chinese firms to buy at prices below world market levels [127]. Mohan and Power (2008) thus caution that mineral extraction will not fundamentally challenge Africa's extroverted relationship with the world economy. This unequal relationship keeps it at a perpetual disadvantage and locked into supplying raw materials to global markets, rather than adding value to its local economies [128]. De Haan and Geenen (2016) also noted that mining cooperatives, intended to support local miners, have in one other sector (South Kivu) done the opposite and become tools furthering the exploitation of miners at the hands of the elite [129].

Hinton et al. (2013) indicates that many of the health impacts from mining are gendered, with women facing additional illness, injury, and stress as well as extreme exertion and exhaustion from very labor-intensive activities (i.e., digging for several hours, hauling heavy loads long distances, bending over in awkward positions) more than men [130]. Tsurukawa et al. (2011) noted that women in mining communities face the ever present risk of contracting dangerous diseases being spread by miners and migrants, including diarrhea, hepatitis, meningitis, bilharziosis, cholera, typhoid, tetanus, typhus, malaria, yellow fever, tuberculosis, musculoskeletal disorders, respiratory disorders and headaches [131]. Moreover, the fact that many forms of ASM are nomadic in nature adds stress to family routines and structures, with women often having to take care of children, orphans, the elderly, and widows in addition to their mining activities [132].

Child labor can also be associated with mining. Amnesty International documented child mining in the DRC and noted that many children drop out of school, and/or are driven by family poverty, to mine for cobalt [118]. Children work in the open, in high temperatures, in the rain, and they report falling sick and "hurting all over" [118]. The International Labor Organization (ILO) even classified child mining for cobalt as one of the "worst forms of child labor," given that it:

- Exposes children to physical and at times psychological and sexual abuse;
- Requires working underground, underwater, at dangerous heights, or in confined spaces;
- Involves dangerous equipment and tools as well as the manual handling of heavy loads;

- Places children in unhealthy work environments that expose children to toxic substances, agents, and processes;
- Necessitates difficult conditions including working for long hours or at night

Often children will carry sacks of ore that weigh more than they do and are also exposed to physical abuse and beatings, whippings, and attempted drownings from security guards. They are also exposed to drug abuse, violence, and sexual exploitation. Children also reported being financially exploited by traders and bosses who refused to even weigh their products, and instead paid substandard and below market rates for sacks of cobalt based on visually estimated weights. The World Bank (2007) writes that while some children may be paid in cash, they are "most often cheated and some are not paid to work, but to simply survive while receiving only basic sustenance as payment."[123]

*5.4 Water*

Water considerations are likely to be one of the largest environmental barriers, as water scarcity is a major barrier to the development of material resources across the world. The International Council of Mining and Metals and the International Finance Corporation have both released a report regarding the increasingly important role of water in the mining sector, especially in newer, remote locations [133]. Multiple mining executives have given warnings that assets will be stranded and investors will walk away unless they deal with water scarcity in key mining regions such as Africa, Australia, and Latin America [134], [135]. Northey et al. (2017) expands on the global interaction between the mining industry and water resources to show that minerals like copper are generally located in regions where water consumption is more likely to long term decrease in water availability [136]. The U.S. Geological Survey's annual exploration review also warns that competing demands for energy and water has increased risks related to energy and water investment and limited growth [98]. This is especially troubling as ore grades continue to decline with mining explorations taking place in more remote locations. In response, the mining sector in Australia, Canada, Chile and South Africa have increased their focus on increasing access and developing new techniques for using desalinated water and renewable energy sources in order to reduce energy consumption and adopt more sustainable energy sources [98].

## 6. Resource Efficiency and a Circular Economy

In this section, the role of technical changes in the recycling and extractive industries are explored.

Changes in the mining and recycling industries need to be better understood as they will have large impacts on the primary resources needed for the renewable energy transition. Reports on the supply and demand scenarios for various temperature mitigation goals state that the exact materials and quantities necessary for the energy transition are dependent on what technologies become popular or more efficient [2], [3], [18]. Despite attempts to limit ambiguity with only basic demand assumptions and multiple climate scenarios, technical changes regarding the sourcing of metals and minerals are not often discussed in the same context as demand needs. With concerns over sudden increases in mineral demand, and exploration projects becoming "more costly and difficult to develop" (USGS 2018), the nature of the mining and recycling industries are becoming increasingly important [98]. Mining reports on business risks by Ernst & Young Global Limited and Deloitte both see technical change as a strategic priority for its role as an enabler across every facet of the business [137], [138]. As such, the ability to develop technologies that utilise abundant metals, aid in primary extraction, improve metal intensity, and/or increase recycling will determine the flexibility and preparedness for various material needs in the future [11].

*6.1 Recycling and Resource Efficiency*

The recycling of metals from end-of-life products can improve the future availability of critical materials, but data on its feasibility is often lacking and needs to be researched [2]. With questions regarding life-cycle and recoverability, many of these technologies have not yet proven to be economically viable in comparison to existing extraction sites. One of the arguments presented by Ali et al. (2017) for resource governance revolves around secondary metal production and the role of recycling in the future. Of particular concern is the potential period when primary metal production may stumble before the infrastructure for secondary metal production will allow recycling to contribute on a meaningful level (Figure 14) [69]. Tilton et al. (2018) claim that price increases for materials can quickly offset recycling shortfalls, but also advocate for R&D, as innovations alone offer the possibility of keeping mineral depletion at bay indefinitely.

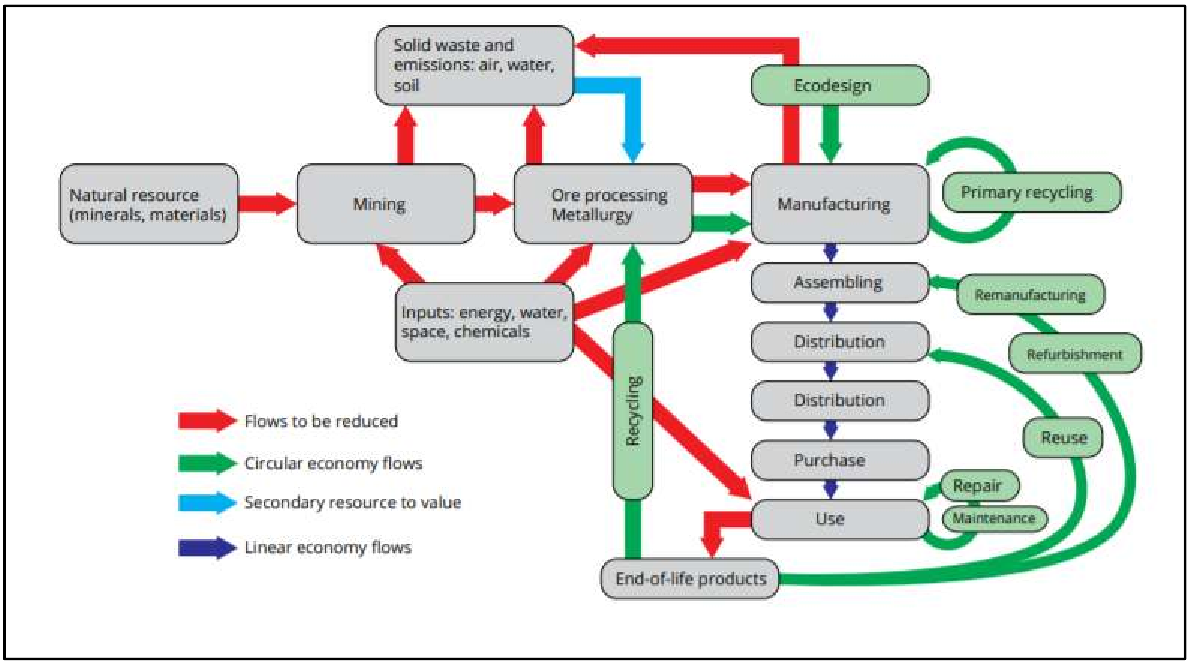



**Figure 14: Schematic transition towards a circular economy for minerals and metals.**
(Ayuk et al. 2019)[139]

Watari et al.'s (2018) claim that recycling can reduce primary demand by 20%~70% for low carbon energy technology is especially relevant when seen in the context of time needed to research and understand recycling challenges [32]. The diverse set of technologies and unknown material mixes makes high recycling rates difficult to obtain for all of the metals included. A disparity between metals contained in technologies reaching their end of life, and what is demanded in new technologies, is also likely to exist in the future. USGS's most recent *Minerals Yearbook: Recycling Statistics and Information* shows that the United States recycled 59.0 million metric tons (Mt) of selected metals, an amount equivalent to 51% of the apparent supply, but only 1% of REE's from end-life products [140]. Jowitt et al. (2018) discusses the unrealized potential of recycling of the REE and how it is possible to alleviate some criticality of certain materials, albeit with extensive research [141]. Institutions such as the Critical Materials Institute have been doing said research and have already won, among other achievements, a Notable Technology Development Award for their acid-free dissolution rare-earth magnet recycling process [37]. Similarly, the National Energy Technology Laboratory's program to recover REE from coal and coal byproducts is already working to scale-up and optimize their extraction methods [96]. Start-up companies like Li-Cycle have started to envision the recycling of lithium-ion batteries to recover lithium, cobalt and nickel [142]. Other research into recycling silver, cobalt, and lithium can prove just as valuable, with the effects on production shown in Figure 15.

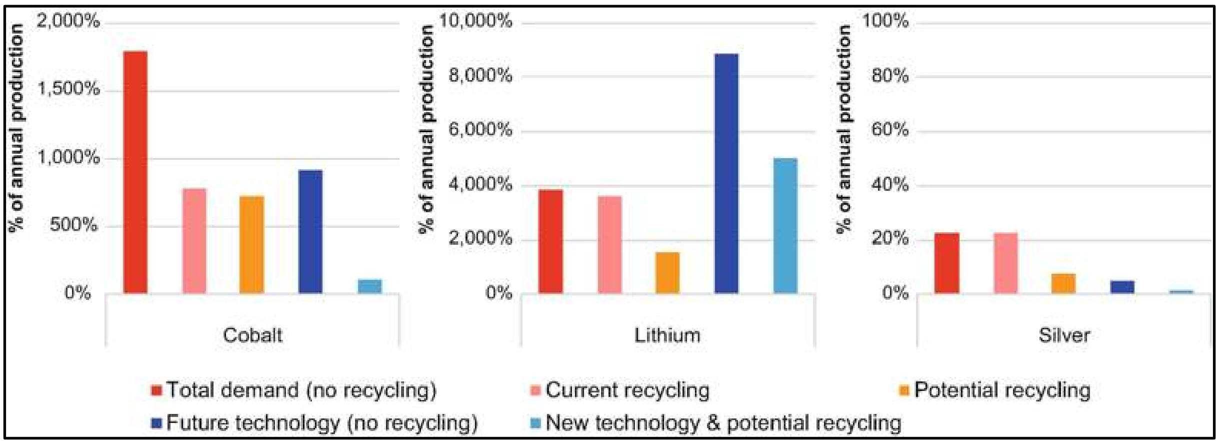



**Figure 15: Annual demand from renewable energy and storage technologies in 2050 compared with current production rates** (note that scale varies across the metals) (Giurco et al. 2019)[7]

*6.2 Innovations in Mining Technology*

The ability of the mining industry to meet supply needs is highly dependent on mining technology, as innovations serve to offset the downsizing in the global mining industry while helping to secure investments [138]. S&P Global's 2019 report on metals and mining trends warns that they expect prices to remain volatile, with fluctuations likely related to developments in China and potentially other government policies and geopolitical risks [143]. The resulting balance sheet conservatism can delay future responses to increases in demand, and do not preclude a flexible and adaptive mining industry [69]. The USGS's 2017 annual exploration review claimed that 2017 marked a global recovery from the trend of decreasing exploration budgets that were reported for 2012-2016, but also claimed that many exploration projects are becoming increasingly more costly and difficult to develop [98]. The depletion of shallow, known deposits has driven exploration companies to remote areas with limited infrastructure, which can create new concerns [98].

Deloitte and EY Global Limited have both compiled lists aiding to identify the necessary trends for growth to offset these challenges and emphasize that the mining industry is in position for a technology-enabled transformation [137], [138]. As reported by McKinsey and Company, advanced analytics, autonomous equipment, and artificial intelligence can help to improve upon the modest 2.8% increase in mining productivity from 2014-2016 [144]. At the same time, finding qualified workers to fuel this transition is a problem, as outlined in The United States' *Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals [72]*. According to the strategy, the mining industry faces a wide array of challenges including an aging and retiring workforce and faculty; a decrease in mining, mineral engineering, and economic geology programs; negative perceptions with respect to the nature of the work; and foreign competition for U.S. talent [72]. These shortcomings once again lead back to Tilton et al. (2018) calling for government intervention to address externalities regarding education, and how important adaptability is for the future [50].

Further seeking to offset some of these trends, the Columbia Center's report *The Renewable Power of the Mine* advocates for the integration of renewable technology to offset expenses, reduce the carbon footprint of mining operations, and update the technical level of operation [145]. As electricity needs can make up 15% of total mine costs (40% if processing is involved), technical changes, like renewable energy installations, can aid in making mining more profitable and attractive to investors while aiding to reduce carbon footprints [145]. This is especially relevant as the GHG emissions from mining operations become more of a concern with higher demands and varied results from life-cycle analyses [111], [146]. The Thabazimbi mine in South Africa used solar integration in 2013 and was able to break even after only 3.6 years [145]. Other similar projects across the world and the "greening of the mines" present opportunities for sustainability and the attracting of a newer, technology-driven workforce.

However, despite potentially game changing initiatives and goals, it is not clear how the mining industry will handle dramatically rising material needs. The U.S. Geological Survey's most recent exploration review shows that gold and silver still accounted for the majority of active exploration sites, and that the renewable materials market is not a priority [98]. Sector wide discussion is likely needed to plan for these magnitude sized increases in demand for various scenarios, while government intervention will also likely be necessary to aid in addressing knowledge externalities.

*6.3 Processing Technology*

The mining and refining sectors will also have to innovate and target new sources to meet demand for materials in the renewable energy transition. Mudd et al. (2017) show that there are likely to be significant volumes of tailings and mine waste that represent potential sources of critical and other metals [147]. Innovations to current processing efficiencies and recoveries could also produce more from existing supply chains, especially in terms of minor by-product capture. With this in mind, input data (anode composition) was collected from 30 refineries from 2014-2018, which produced 37% of the world's electro-refined copper, and were analyzed to calculate by-product potential [72], [148]. Table 2 summarizes the estimated world by-product potential in copper anodes of critical minerals and compares the potential to world production [148]. It is clear that processing innovations could unlock significant production of selenium, tellurium and bismuth from the existing copper supply chain, and that other such changes can also have meaningful impacts.

**Table 1: . Estimation of critical mineral potential in the world's copper supply chain**

| Critical Mineral [##] | Estimated Potential in Copper Anodes (ton/year) | World Production (ton/year) |
|---|---|---|
| Selenium | 8300 | 3300 |
| Tellurium | 2200 | 420 |
| Bismuth | 4900 | 14000 |
| Antimony | 6200 | 150000 |

(U.S. Geological Survey 2019)[9], [72]

## 7. Markets and Modeling

In this section, supply and demand considerations are examined in the context of full material supply chains.

The assumed availability of mineral commodities during the energy transition is often simplified instead of contextualized through a framework of supply chain considerations. Cumulative demand scenarios presented in mineral reports, such as *Growing Role of Minerals and Metals for a Low Carbon Future*, *Responsible Minerals Sourcing for Renewable Energy*, *Requirements for Minerals and Metals for 100% Renewable Scenarios*, show possible market failures where demand is routinely positioned to exceed production trends [2], [7], [18]. This disconnect has resulted in Ali et al. (2017) and others to call for resource governance as a means to "reach consensus on international targets for global mineral production" [69]. While an important paradigm shift from literature investigating life-cycles and energy return on investment, the focus on supply and demand lends itself to an alarmist attitude. The nature of energy security requires considering dozens of variables that impact material needs and an awareness of multiple points of failure along supply chains [149].

Externalities corresponding to the energy transition, including sustainable mineral production, manufacturing efficiency, recycling, and the research/education necessary for substitutes, are especially important considerations and should always be discussed in conjunction with supply needs. From a market oriented perspective, Tilton et al. (2018) attempt to rebuke "pessimistic" views about material scarcity by contesting that "shortages are temporary and do not pose a serious long-run threat to human welfare" [150]. Tilton et al.'s (2018) comparison of the energy transition to "peak oil" and reminders that higher prices "foster supply and curb demand" might appear passive, but they also acknowledge that government intervention is needed to address serious market failures such as environmental policy and research into recycling. ISF's report explicitly states that demand from renewable energy and storage technologies could exceed reserves for various minerals, but its' "key intervention points" responsibly revolve around recycling and awareness of sustainable sourcing [18]. Similarly, while Månberger & Stenqvist (2018) found lithium and cobalt reserves to be incompatible with the IEA's B2D scenario, they conclude that those considering a metals criticality should "focus more on how to reduce vulnerability by developing technologies that utilize abundant metals, improve metal intensity and/or increase recycling" and that metals may be perceived as more critical in the medium to long-term today than is actually the case if policies that reduce vulnerabilities are implemented [11].

Further considerations that highlight the complexity of markets and externalities are presented in analysis of rare earth markets by Sprecher et al. (2015, 2017) following the 2010 REE crisis. The United States sole rare earth supplier, Molycorp, despite having a $6 billion dollar market evaluation, filed for bankruptcy in 2015 due to the popularity of rare earth alternatives and the easing of China's export rules, both of which caused a rapid decrease in REE prices [151], [152]. Sprecher et al. (2017) found that annual substitution rates reached 10% of total demand, while non-Chinese primary production increased only at a speed of 4% of total market volume per year [97]. Subsequently, "recovery" from the disruption only took two years, and the crisis was unable to induce an appreciable degree of recycling. This disconnect implies that sustained material constraints might be decisive in the passive implementation of circular economies and internalization of some externalities [97].

For actual material needs, the uncertainty of future technology makes demand predictions better at identifying trends than exact quantities. Månberger & Stenqvist (2018) caution that technological development has previously enabled metal intensities to improve, and that historical estimates of technologies maturing to the point of no further improvement have been wrong (although not always) [11]. Grubler et al. (2016) and Sovacool (2016) further highlight this uncertainty by discussing the complex nature of measuring what exactly an energy transition entails and how long it can take [153]. With these uncertainties, demand predictions are not meant to act as explicit guides to the transition. Cumulative demand ranges of ≈24,000 tons - 700,000 tons for silver are not at all indicative of uncertainty or bad modeling but, as the report states, are supposed to "engender a broader dialogue between the mining and metals constituency and the climate change and clean energy community" [2]. The intrinsic ambiguity of predicting the material needs for the energy transition is not unexplored, and is one of the reasons that it is more difficult to estimate a forward price curve for lithium that for crude oil [154]. This uncertainty makes investment decisions by market participants, as well as research, difficult. As such, the United Nations' proposal for *Mineral Resource Governance in the 21st Century* is a much stronger approach than calls for "material quotas" and production goals. Instead of trying to understand a multitude of ever changing variables, the UN proposal, and the World Bank's 2017 report, suggests strengthening businesses, industries, and governments so that they can be adequately prepared to adjust for material needs as they develop. This adaptability occurs through not only increased transparency, but also through relevant government policies. Not only does this allow for healthy development across multiple sectors, but is also one of the only ways to ensure that material needs are adapted to appropriately instead of over/underestimated.

### 8. Policy Pathways and Global Political Trends

In this section, geopolitical trends regarding the nature of the energy transition and their potential impact on supply chains are explored.

The geopolitical considerations of renewable energy have not been commonly investigated despite the far-reaching influence of material supply chains and future energy needs. IRENA's report on the geopolitics of the energy transition lays the technical foundation for how the transition will cause disruptions, especially in regards to fossil fuel flows and renewable energy technology, but doesn't focus on the implications of already enacted policy and strategy [4]. With the multifaceted nature of the energy transition, it is worth examining both the larger implications of the political shifts, and the smaller legislative trends that are already aiding in geopolitical changes. Bazilian et al. (2019) explores four possible geopolitical trajectories for the energy transition. Using these "Four Futures" (Figure 16) as a lens, examinations of corruption, conflict, and trade can be used to better understand the political challenges of future policymaking [155].

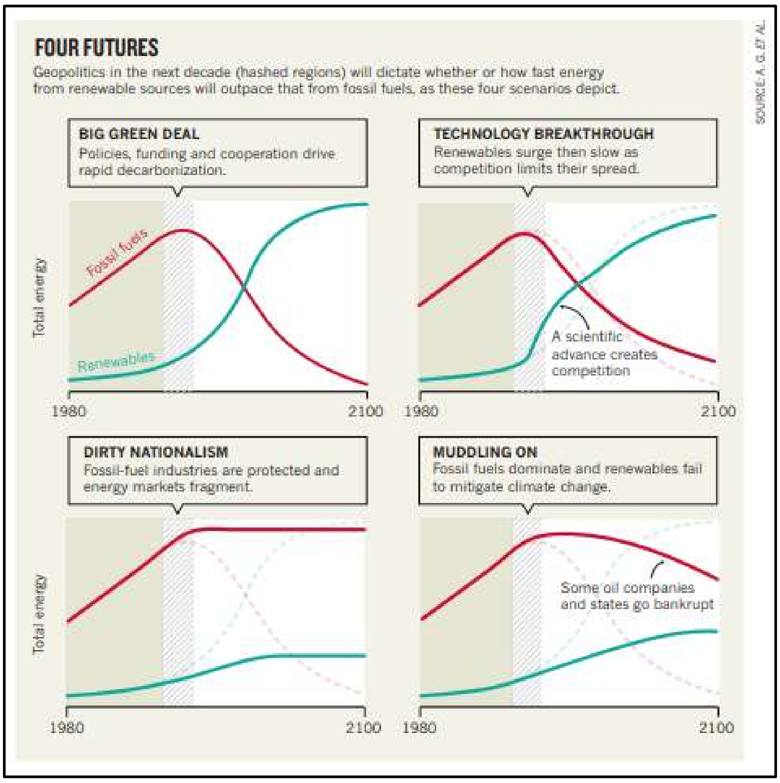


**Figure 16: Four global low-carbon futures**
(Bazilian et al. 2019)[155]

*8.1 The Big Green Deal*

A "Big Green Deal" scenario, with a concerted international policy drive, aligns well with the Paris Agreement and the United Nations Sustainable Development Goals, but might not be the scenario the world is building towards. The 'bottom up' structure of the Paris Climate Agreement, requesting that all parties "put forward their best efforts", succeeded in adoption, but cannot ensure that the appropriate material policies are being built [1]. The United States internalized approach to energy and rejection of anything that might obstruct development, including limits on GHG emission, (Executive Order 13783), is one of many nationalistic energy trends that will likely cause material disruptions and prevent the adoption of a "Big Green Deal" [156], [157]. President Trump's withdrawal from the Paris Accord came with the justification that the accord would cost the United States "$3 trillion in lost GDP and 6.5 million industrial jobs"[158] while giving China and India a political edge in energy. This perspective is not indicative of appropriate acknowledgment of externalities and instead highlights a problem raised by Tilton et al. (2018), where "private firms cannot be expected to curtail their pollution to socially optimal levels unless public policy requires their competitors to do the same" [150]. From a low-carbon materials perspective, this means that the nations like the United States are not moving towards decarbonization by adequately investing in the technologies and material supply chains that will let them operate successfully in the low carbon future. The Big Green Deal, which is a best-case scenario for many nations, becomes increasingly difficult to achieve as mining operations, recycling programs, and policy driven change have less time to take effect and enact the change necessary to successfully accommodate material demand and an optimal low-carbon transition.

*8.2 Muddling On*

Indicative of the "muddling on" future, a lack of focus on critical material supply chains, and their environmental and social implications, only slows down a nation's ability to adapt a beneficial renewable energy strategy. China leads the world in renewable energy investment, with $126.6 billion in 2017, but the China Global Energy Finance database shows that coal projects accounted for up to 42% of China's overseas investment in 2018 [159], [160]. China's control of renewable markets while being involved in hundreds of coal projects in other countries (BRI) is even counterproductive to reducing material vulnerabilities for other nations. The implementation of low-efficiency coal plants passes structured, monetary risks onto developing countries and limits their ability to enact policies focusing on recycling, material development, metal use [161]. A report by Carbon Tracker claims that 40% of China's coal power stations are already losing money, and that the number could rise to 95% by 2040 due to the cost of complying with air pollution regulations and a rising carbon price [162]. As the coal plants China is building in other nations are of even worse quality, this is a troubling trend [161]. Financial implications are reflected by the Institute for Energy Economics and Financial Analysis' estimates that US$150 billion of asset impairments have been incurred by European utilities over the period 2010-2016 for not anticipating renewable energy trends [162], [163]. This investment into depreciating assets and high-carbon energy can only be seen as a step backwards when considering what changes need to be enacted for a low-carbon future. The loss of capital is significant when considering the time scale necessary to open mines, international trading routes, create entire recycling industries, and enact general changes necessary to accommodate future material demand.

*8.3 Dirty Nationalism*

Calls by the United Nations Environment Programme for adaptable resource governance as a way to aid developing nations and mitigate the shocks of future supply are well founded when considering nationalistic trends exhibited by some of the world's largest economies [139]. Gaps in mapping relevant mineral/metal resources and the disconnect between production activities and reserve levels are especially relevant for nations that are part of the BRI, as they are subject to large risks [2], [69]. However, China's Development Research Center reminds the world that, as a major producer and the world's largest consumer and trader of resources, "there is no global resource governance without China" [164]. Together, this mentality, US-China trade wars, and rising nationalism make cooperative transitions increasingly difficult to achieve and "dirty nationalist" increasingly likely [161], [165], [166].

International competition for limited resources can create material shortages and policy related, ethical considerations for the energy transition. IRENA's description of the shift to renewables as a "energy transformation" is especially apt when reminded that "fossil fuels have been the foundation of the global energy system, economic growth, and modern lifestyles" [4]. With the rise of renewable energy, each nation's ability to adapt to the transition depends on how exposed they are to changes in fossil fuel trades and their position in the clean energy race (Figure 17) [4]. Therefore, the "dirty nationalism" future see tensions rising between groups who seek to control the markets and materials needed for the energy transition. The formation of cartels in the vein of OPEC are a very real possibility, but can also be mitigated by the development of resources in varied countries. Concerned with the alliances China is making through the Belt and Road Initiative, the United States has already passed the BUILD Act in 2018 to help "developing countries prosper while advancing U.S. foreign policy goals and enhancing U.S. national security interests" [167]. China's restriction of rare earths in 2010 after the Senkaku boat collision incident set precedent on how supply and control of these critical resources can be leveraged [168]. Critical material strategies created in the following years changed from trying to create a unified energy policy, into goal oriented strategies necessary for "economic prosperity and national defense of the United States" or "essential building blocks of the EU's growth and competitiveness" [8], [72]. China's embargo even extended political alliances to the point that there is a Trilateral EU-US-Japan Conference on Critical Materials for government officials, industrial representatives, and researchers to exchange information on recent initiatives and future challenges [169]. With China developing trade alliances and trying to create a world where "all roads lead to China", increased nationalistic tendencies will only aid in creating a future where the low-carbon energy transition creates conflicts over resources [170].

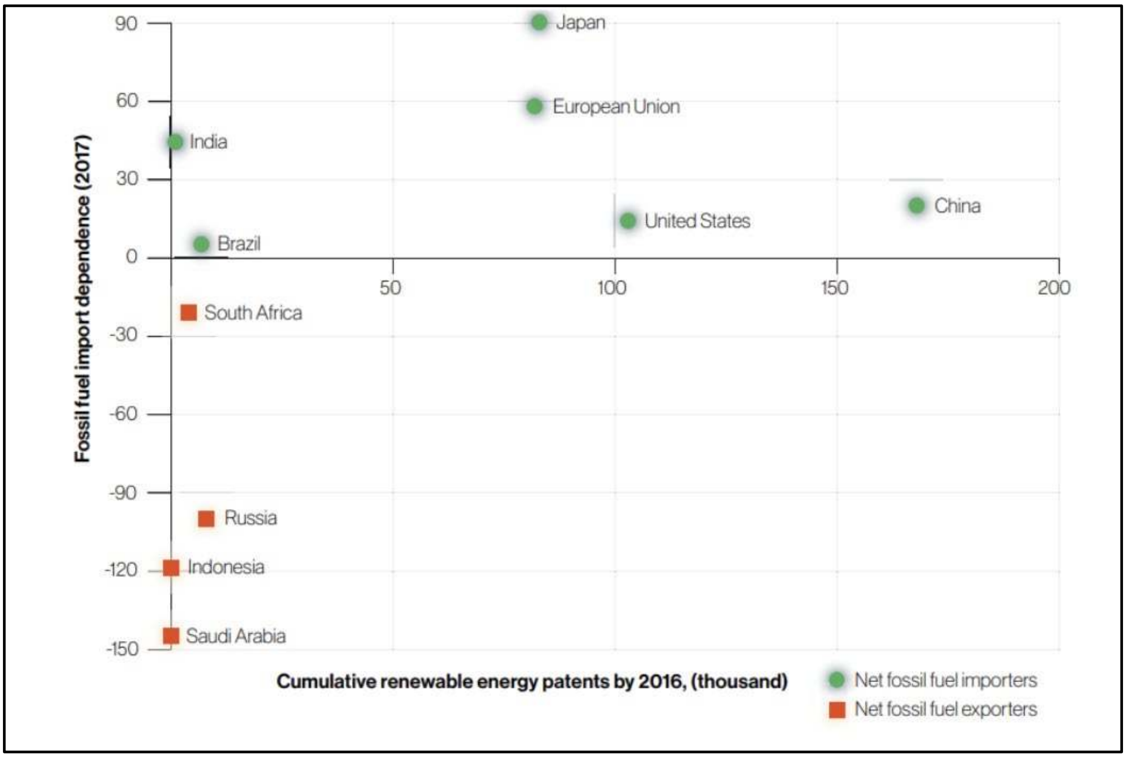



**Figure 17: Impact of the energy transition on selected countries and groupings**
IRENA (2019)

*8.4 Technology Breakthroughs*

The “Technology breakthroughs” scenario sees technology being withheld as an asset, and limiting the spread and ease of low-carbon adoption. Problems with China stealing intellectual property and the importance of patents are already fostering a sense of competitiveness and are indicative of this scenario. Fortune reported this year that one in five U.S. corporations say they have had their intellectual property stolen by China, and a U.S. Trade Representative has estimated the annual loss to China is between $225 billion and $600 billion [171]–[173]. With the rise in prominence of renewable energy, this trend is beginning to be seen in other areas as well. Chinese turbine maker Sinovel Wind Group Co. was ordered to pay $59 million in 2018 for stealing trade secrets, and a theft from a Scottish wave-power company in 2011 went forgotten until a very similar renewable project appeared in China a few years later [171], [174]. The relative number of patents from each nation are shown in Figure 18, although the majority of patents are still held by individual nations, such as Germany in the EU [4]. Longitudinal studies have also shown that China’s share of patents in the renewable energy sector has increased in the last decades [4], [175]. However, such studies do not take the quality and significance of patents into consideration and may therefore overestimate China’s innovative leadership and control of renewable energy technologies. From a material perspective the role of technology breakthroughs become more apparent when considering what types of material investments various nations have been making. For China’s interest in manufacturing renewable technologies, securing supply chains is especially important in facilitating their role in the low-carbon future. Similarly, the United States large share of patents relative to investment reflects their interest in developing material substitutes, as they have import reliance for a troubling amount of materials (Figure 11).

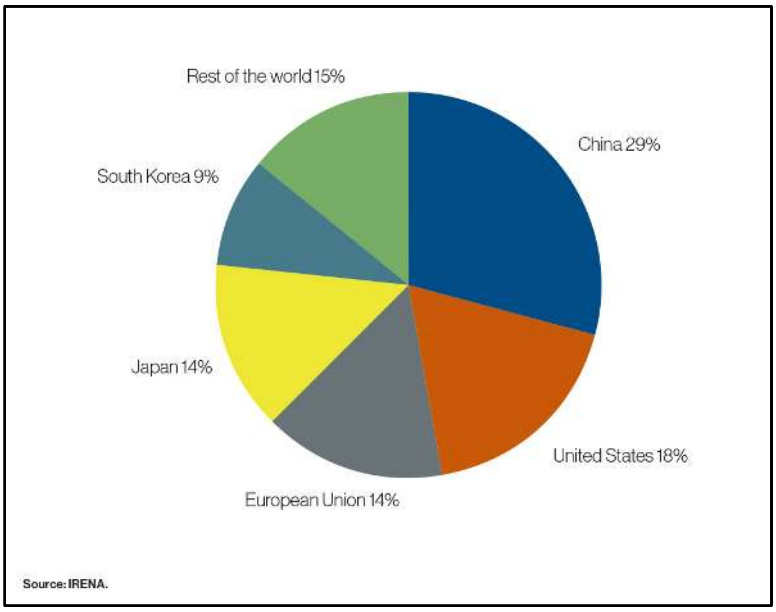



**Figure 18: Cumulative share of renewable energy patents end 2016**
IRENA (2019)

### 9. Conclusions and Future Research

This review was conceived as a problem-oriented perspective in order to identify gaps in strategy and policy relating to materials of the low-carbon energy transition. Although investigations into material needs have shown that physical scarcity will not be a limiting factor, it has become a much more complicated issue with environmental, social, political barriers to extraction and material security. China's investment strategy, the pace of renewable energy integration across the world, and the general development of critical materials have shown that a passive interest in a low-carbon economy is not enough to achieve environmental goals. Active policy changes will be necessary to ensure that renewable technologies are adopted at a pace that both facilitates growth and allows for each nation to prepare for its eventuality. For economies across the world, this means solidifying pathways towards resource development, recycling programs, healthy extractive industries, and being aware of the geopolitical challenges that come with diverse energy needs. For most nations, there is a great deal that still needs to be understood about the transition, and this review serves to highlight some of these questions. More focused investigations into decarbonization, material security, and technical challenges all need to be conducted to better understand how policy can adapt and respond to these challenges.

To further these objectives, and with the understanding that the low-carbon transition requires collaboration and an interdisciplinary approach, the following are defined as areas for future research:

- Undertaking further analytical work on the role and scale of metals and minerals in a low-carbon future will be required to create effective policy and mitigate risk. Uncertainties surrounding resource mapping, material needs, energy needs, and technological changes have broad influences that need to be understood and managed, especially in the context of developing nations. The disconnect between resource mapping and the role that renewable energy will play in Africa, South America, and countries parts of the Belt and Road Initiative creates serious information gaps for both international dialogue and domestic policy decision-making. It is also uncertain how much demand from other sectors will increase or decline and what the resulting aggregate demand will look like.

- Technology research, like that of the CMI and many other organizations, will also be essential in addressing bottlenecks, whether through the identification and design of substitute materials, improved recycling, or completely new technologies. Several of the CMI "Grand Challenges" are directly related to the issues discussed in this paper, including anticipating which materials may go critical.

- Developing new financial instruments in the relevant commodity markets will help provide some level of risk mitigation and mandate increased levels of transparency. The largely inflexible and slow response nature of commodity markets presents numerous points of impairment for the energy transition. A better understanding of shortcomings and awareness of mitigating options will allow markets to sustain energy growth and development.

- The role that developing technologies will play in the mining industry need to be explored and contextualized. Possible changes in transparency through Blockchain and efficiency innovations brought on by artificial intelligence, autonomous mining, and mining engineering all present opportunities and challenges for future development and resource management. Furthermore, defining and establishing sustainable mining practices need to be understood and properly incentivized. Failure to do so may trigger a backlash and opposition that reduce supply.

- Researching and developing a harmonized framework for carbon accounting and science-based climate target-setting along minerals supply chains that enables supply chain partners and end consumers to adequately track and collaboratively reduce emissions from mining, beneficiation, transportation, and other related processes.

Aside from future research, there are policy changes that can help to mitigate potential challenges across mineral and metal supply chains. For nations facing large geopolitical shifts, exploring these considerations and adopting relevant policies can aid in successfully navigating the energy transition:

- Continued monitoring of governance metrics (through both the Worldwide Governance Indicators and the NRGI Index), and open dialogue with developing nation will be essential in properly supporting countries involved in the energy transition. Transparency with supply chains and the implications of legislative actions need to be considered when developing policy that affects the wellbeing of those in other nations. These considerations are also relevant in establishing dialogues between mining companies and government agencies in charge of plans for countering and preventing conflicts. In most countries, these dialogues are not well-established, and must be linked to wider efforts of conflict prevention and development.

- Mapping the new geopolitical landscape, or at least the changes to its contours will be essential to informing foreign policy and diplomacy. New or repurposed UN bodies or Conventions may need to be put in place, and the potential role of each nation needs to be explored.

- Integration and sourcing of information from previous measurement efforts of energy security and material development will likely prove valuable in both political and technical approaches. Lessons on mineral development, such as those presented by Argentina and Chile, may prove invaluable to Bolivia's development of their own lithium resources. Other such relationships, and lessons on import reliance and supply chain difficulties from past iterations can provide insights into the future development. As such, nations should focus on developing bilateral and cooperative relationships for material and energy development.

- Although trade policies, including tariff-setting mechanisms and dispute mechanisms are in place through the WTO, they will need to be augmented and refined to tackle the new patterns and scale in trade for certain of the minerals.

Ultimately, achieving a low-carbon future will depend on a robust, transparent, accountable, and sustainable mineral and metal foundation. Better grappling with how that foundation is conceived by the research community is an essential first step towards reaching the dual goals of decarbonization and responsible mineral extraction.

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