The transition to a low-carbon environment is rapidly accelerating and with it the potential for severe environmental and social degradation. The extraction and processing of key materials have already begun to affect developing economies, and policy changes are essential to ensuring a just transition.

Building the future

The transition to a low-carbon energy system has the potential to deliver multiple benefits to society and the environment. These benefits range from decreasing climate-related deaths to increasing life-saving energy systems in developing economies, as well as abstract benefits such as addressing geopolitical tension and fostering collaboration. As the transition accelerates, policymakers have begun to examine the contours of the shift and have recently paid attention to the material requirements of new and developing technologies. This follows the fact that the future energy system, under many different scenarios, will be more material intensive than the current one.1 The rapid diffusion of technologies such as lithium-ion batteries, wind turbines, and solar photovoltaics ensures that these minerals and metals will become essential to ensuring successful low-carbon transitions and will remain the focus of future security concerns.

Yet as different nations begin to develop aggressive climate change policy and trade agreements, comparatively little progress has been made in addressing the detrimental effects of rapid and continuous mineral extraction and processing.2 The mining industry has a long history of environmental degradation, and many questions remain around optimal policy solutions to address the “resource curse.”3 Sustainable development concerns to date include the use of child labor in cobalt sourcing, the impact of lithium extraction on nearby ecosystems, copper pollution in the vicinity of mines, and the toxicity of rare-earth elements, along with other impacts from the materials of the energy transition.4,5 Given that large demand increases are likely, there exists a significant risk that future supply shocks will create conditions where damaging mining prospects become more attractive—and environmental, social, and governance considerations get pushed aside.

It is therefore important to acknowledge the inherent tensions that exist between building a sustainable future and not managing or understanding the sources and materials with which it is built. Although the energy transition is critical to addressing the climate challenge, care must be taken to minimize new risks and acknowledge the possibility for unintended consequences. It is up to the countries that are driving these technological changes to help ensure that the materials are managed in a way that enables the transition instead of tarnishing its goals.

Unintended consequences of mineral sourcing

Although many of the key minerals required for a low-carbon energy transition are not uncommon in Earth’s crust, the current footprint of production is highly concentrated (Figure 1) and often heavily reliant on developing nations or fragile supply chains.6 The geographic concentrations of minerals can lend to this lack of diversity, but it can also be partially explained by unbalanced foreign direct investments and relatively limited interest by international mining companies.7

For example, areas such as the Lithium Triangle (Bolivia, Chile, and Argentina) contain 64% of the world’s lithium resources, but even with large demand estimates, they account for only half of global production.8 Bolivia alone has the world’s largest supply of lithium, more than all of the current global reserves combined, but investors are hesitant to help the nation develop its industry because of its historical instability and the technical burdens they would have to help the country overcome.9 To this day, Bolivia’s lithium production remains virtually non-existent, whereas Chile’s production is struggling from a lack of regulation that would help investors gauge risks.8,10 For other minerals and metals around the world, this is often made worse by opaque markets and poor price discovery to inform appropriate investment or production.

Unfortunately, many developed countries are highly import reliant on many of these minerals and metals, reflecting a trend that has shifted the burden of resource extraction to developing countries—all while the US and other nations focus on more profitable, reliable materials. As an example, the US has doubled the number of minerals it is 100% import reliant on over the last 60 years while also doubling the number of minerals that it is at least 50% import reliant on (Figure 2).8,11 Of the 35 critical minerals identified by the US today, 14 had a 100% net import reliance in 2020, and 14 additional minerals have a net import reliance greater than 50%.8 Yet despite this steady growth in imports, the US mining industry has not adapted or expanded its portfolio. In 2020, US metal mine production totaled only $27.7 billion, 38% of which came from gold as a result of increased prices, and copper, iron, and zinc made up most of the rest.8

For the US and other developed nations, this mineral dependence can lead to a slowdown of renewable technologies or limit their ability to engage in climate action, but for other nations this can lead to much more devastating impacts. Mineral security is not only an issue from the perspective of an importing country—it can come in the form of environmental or social issues as well. The US’ and other nations’ ability to drive demand but
the nation’s vast mineral reserves and that these businesses directly contributed to conflicts for favorable rates and purchase agreements. More recently, reports have found as many as 255,000 artisanal cobalt miners in the DRC, 35,000 of whom are children working in exceedingly harsh and hazardous conditions to produce the materials many people use in their $100,000 electric vehicles (EVs) and other “clean” technologies. Similarly, mining for lithium has been criticized in Chile for depleting local water resources across the Atacama Desert, destroying fragile ecosystems, and creating unknown, long-term environmental impacts even though the nation exports most of what it produces to support electronics and batteries in other countries. The production of cadmium (used in semiconductors and photovoltaics) has also been linked to groundwater and agricultural soil contamination, along with worker exposure to hazardous chemicals, but this is rarely discussed among solar advocates or by those who lobby for green legislation. The mining of rare-earth elements has also resulted in chemical pollution from ammonium sulfate, ammonium chloride, and radioactive elements that now threaten rural groundwater aquifers, but the associated tariffs, monetary costs, and import reliance are almost always the focus of newspaper headlines and discussions.

Opaque supply chains pose challenges
Considering entire supply chains—from the initial steps of extracting ore to the manufacturing of highly complex end products—is important to understanding the risks and opportunities for different minerals and metals. In some cases, these supply chains are being enabled by companies that refuse to enact due diligence and by nations that have starkly rejected many of the principles of sustainable development. This most notably includes China, which although not always directly in control of mining sites, has coordinated with and invested in struggling companies and nations for dominant positions with many of the world’s critical minerals.

The majority of the cobalt in the DRC, the lithium drying up Chile’s water, and even the copper used in more common electronics are being purchased and processed by China, which has taken a “don’t ask, don’t tell” approach to sourcing. China has remained a primary investor in lithium around the world, partially through state-owned enterprises, and now dominates the lithium-ion battery supply chain to account for 80% of the world’s raw-material refining. Even in situations where the nation can’t manage a resource, it often enters into purchase agreements or loans, which analysts worry will act as a debt trap to force impoverished nations into being more accommodating. Now that China recently cancelled the DRC’s overdue $28 million loan in early January and the DRC signed an memorandum of understanding for the Belt and Road Initiative while being provided another $17 million in support, this analysis seems more topical than ever.

Once the materials get mixed into normal supply chains in China or other parts of the world, then it stops being easy to assign blame or understand impact. As a result, it is clear that these trends will not go away on their own. Instead, the shift in demand for materials to build and power a low-carbon energy environment represents an opportunity to improve resource governance. To enable sustainable development, to mitigate environmental problems, and to successfully navigate the energy transition, a more proactive approach is needed—one that improves conditions for mining around the world while building out more diversified supply chains in high-income countries.

How do we fix global mining and production issues?
The extraction of mineral resources plays a dominant role in many developing nations; for example, mining regularly provides more than 25% of countries’ income in parts of sub-Saharan Africa, Asia, and South America. Few industrial activities are as capable as mining of influencing the well-being of a country or providing stable enough income to raise the standards of living, teach lasting technical skills, and provide a jumping-off point for manufacturing and service sectors. Because of this, the energy transition and its underlying material needs
undoubtedly create opportunities for developing nations, but only if they’re managed properly, ideally in a multilateral manner.

At the same time, nations such as the US and Canada are increasingly motivated to strengthen domestic supply chains as a result of lessons on import reliance from coronavirus disease 2019 (COVID-19). In these countries, a growing resource-extraction sector could help provide a transition for workers in various industries that are facing declining employment, such as oil and gas, and could support a technical sector that hopes to lead through innovation. Projects such as lithium mining in Nevada are moving forward in response, but better care needs to be taken to ensure that proper community consultation is completed.18

A sustainable and secure path for the energy transition and for mineral security is possible, but it will not be achieved with the same historical playbook. There is still time, albeit fleeting, to make the requisite changes and enable policy and regulation to keep pace with the rapid technical needs. To this end, we offer the following five areas of prioritization:

1. A multilateral approach to good governance across supply chains: this will require the public sector in developed countries to make minerals a key part of their approach to low-carbon goals and therefore put in place responsible sourcing and tracking methodologies. The private sector will need to work toward ensuring that its own supply chains are aligned with these guidelines. For the US, this would mean bringing the relationship between the mining industry and the energy transition to the forefront of the discussion and building industrial policy into action plans such as the Green New Deal.

2. Dramatic improvement and support for markets and trade: integrating good governance, transparency, and market design will go a long way to getting better market signals for investment, as well as hindering “bad” products from entering supply chains. The standardization of environmental, social, and governance reporting by mining and processing entities is a must. The fact that these companies often serve as the only source for mineral disclosures (and that there are minimal requirements on what they must disclose) is untenable in the modern age.

3. Real focus on artisanal and small-scale mining (ASM) by companies or governments: in developing, mining-focused economies, the standards of living and societal benefits are deeply tied to overarching policy frameworks of ASM. ASM has often been viewed as a secondary consideration, and local regulations often ignore or dismiss the large portions of the population that depend on it for their livelihood. The experience of working together with artisanal gold miners and communities in parts of South America has shown the mutual benefits to producers and purchasers and could be replicated in other regions.

4. Work toward sustainable and low-carbon mining practices: the mining industry needs to modernize and start integrating carbon-reducing technologies. This can be at both the level of research, development, and deployment and the institutional level, including new best practices for siting, renewable electricity integration, and increased efficiency. Pilot programs with integrated renewable technologies (e.g., solar panels for powering the mine and EVs for trucks and equipment) have shown great promise and could be expanded.

5. A refined approach to national security: it is important to move away from stockpiling and static approaches to material needs. From a national perspective, this can also include moving toward procurement policies, internal and security agreements, or generally more transparency about national needs and support mechanisms for different industries. This can take the form of mining-specific legislature or an executive order such as the one President Biden signed to help secure supply chains and find actionable solutions that are specific and tailored to the US’ needs and values.13

Many responsible governments, investors, suppliers, and consumers are becoming aware of the untenable nature of anonymous, import-dependent supply chains. This reiterates how creating and managing the material foundations of a low-carbon economy will require a multifaceted approach. Yet, the complexity of multiple stakeholders and international production also creates an opportunity for positive change. There are multiple groups who have the power to exert pressure and ask the types of questions that ensure that we build a sustainable, low-carbon future for everyone’s benefit instead of just a privileged few.

**AUTHOR CONTRIBUTIONS**

J.L. conceptualized and investigated the initial scope while writing the original draft. M.B. and S.H.-S. provided resources for research, contributed to the original draft, and aided in visualization and conceptualization. J.L., M.B., and S.H.-S. all
worked in reviewing and editing the draft to its final form.

REFERENCES


