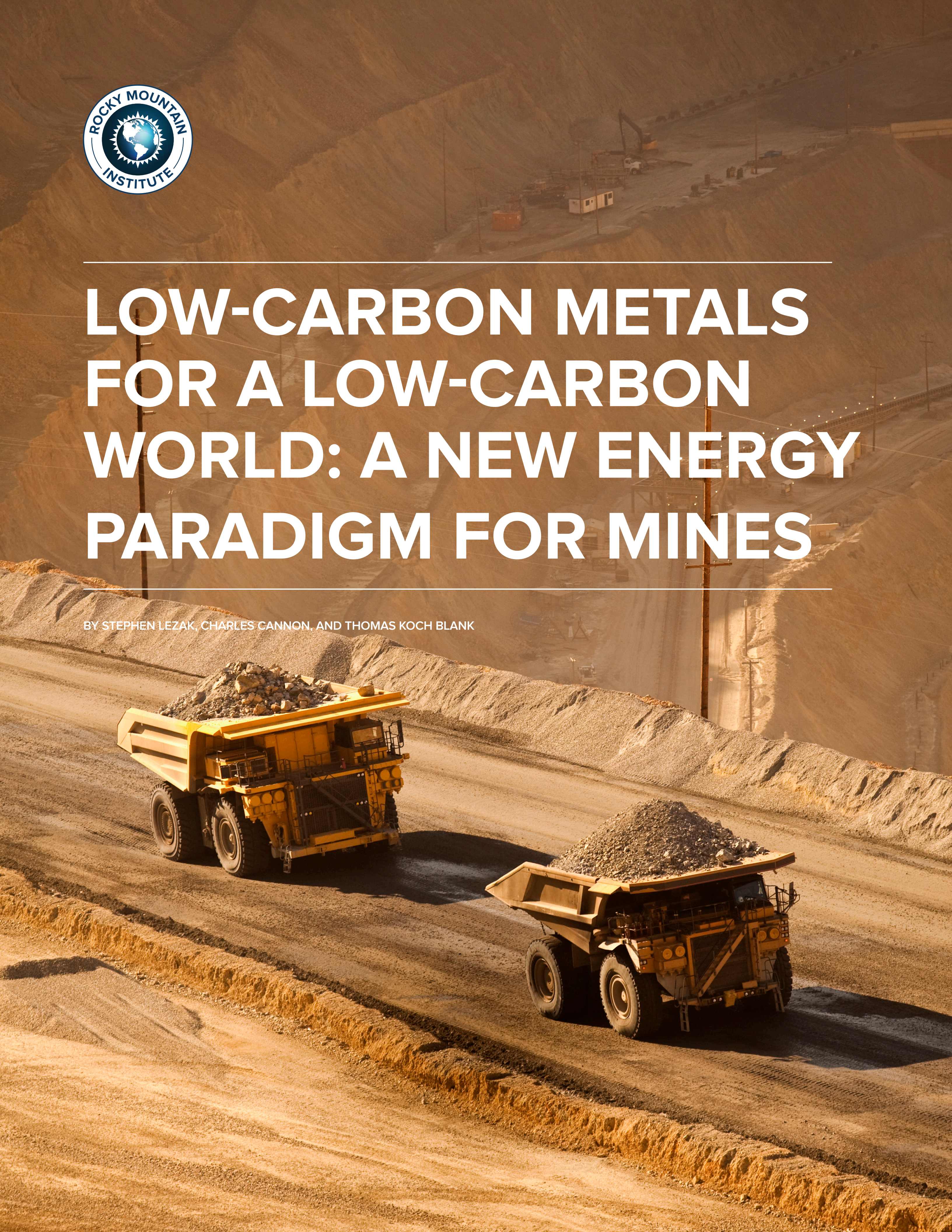


ROCKY MOUNTAIN INSTITUTE

# LOW-CARBON METALS FOR A LOW-CARBON WORLD: A NEW ENERGY PARADIGM FOR MINES

BY STEPHEN LEZAK, CHARLES CANNON, AND THOMAS KOCH BLANK

# AUTHORS & ACKNOWLEDGMENTS


## AUTHORS

Stephen Lezak, Charles Cannon, and
Thomas Koch Blank

** Authors listed alphabetically. All authors from Rocky Mountain Institute unless otherwise noted.*

## CONTACTS

Thomas Koch Blank, **tkochblank@rmi.org**
Charles Cannon, **ccannon@rmi.org**



## SUGGESTED CITATION

Stephen Lezak, Charles Cannon and, Thomas Koch Blank, Low-Carbon Metals for a Low-Carbon World: A New Energy Paradigm for Mines, Rocky Mountain Institute, 2019, **http://www.rmi.org/url here**.

*All images from iStock unless otherwise noted.*

# ABOUT US

## ABOUT ROCKY MOUNTAIN INSTITUTE

Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; the San Francisco Bay Area; Washington, D.C.; and Beijing.

# TABLE OF CONTENTS

# EXECUTIVE SUMMARY

**The production of industrial metals accounts for over 10% of global greenhouse gas emissions. Extensive modeling of renewable energy installations at mine sites, grounded in detailed case studies, shows that mining operations could achieve 45% renewable electricity while improving financial performance and increasing market resilience.**

A low-carbon future requires low-carbon minerals. Copper, iron, lithium, cobalt, iridium, aluminum, nickel, and zinc—these resources are the building blocks of a sustainable and climate-stabilized world. Renewable energy technologies, including solar panels, wind turbines, and electric batteries, require these metals to be available at low cost to compete with fossil-based alternatives.[1] But to extract and refine these materials, producers rely upon some of the world's most energy-intensive industrial processes.

Taken as a whole, the production of these minerals accounts for over 10% of global greenhouse gas emissions.[2] And in recent decades, the energy intensity of producing critical metals such as copper has multiplied several times over as the earth's richest geologic deposits become exhausted.[3] This trend will continue into the 21st century as resources become progressively scarcer.[4] The future of the clean energy transition depends in part upon how metals producers can manage this emerging energy crisis.

The mining industry took centuries to replace hand power with horsepower and horsepower with fossil fuels. The transition to a sustainable energy paradigm will also take decades. But the threat of catastrophic climate change requires that the mining industry act swiftly. Capping global warming at a sustainable level will require metals producers to achieve near net-zero emissions by 2050. Decarbonizing the global mineral value chain requires **(1) innovating new production techniques, (2) undertaking efficiency reforms, (3) electrifying production, and (4) investing in renewable energy** to transform rock into metal using 21st-century metallurgical processes.

Rocky Mountain Institute (RMI) has undertaken an analysis of how renewable energy technology can yield high returns for miners at low risk for investors. Drawing on over 50 individual technoeconomic models anchored in real-world case examples, this investigation suggests that many, if not most, of the world's mines could achieve 45% renewable electricity while improving financial performance, increasing resilience, and protecting the health of miners from the toxins in fossil fuels.[5] Undertaking this energy transition is critical to ensuring that 21st-century mining firms continue to provide value to shareholders and generations of stakeholders.

# INTRODUCTION

In the Paris Climate Agreement of 2015, the members of the United Nations committed to limit global warming to 1.5 degrees Celsius (°C) above pre-industrial levels.[6] Meeting this target requires a large-scale mobilization of political and economic capital to accelerate the process of replacing dirty energy infrastructure with low-carbon energy sources. Although these new technologies will reduce demand for fossil fuels, they require a rapid increase in the production of the minerals that form the basic inputs of a low-carbon society. According to a recent World Bank publication, "the clean energy transition will be significantly mineral intensive."[7]

Consider copper. Humans have been smelting and casting copper for thousands of years, taking advantage of its relative abundance and malleability.[8] But since electricity transformed modern life, copper has been prized for its conductive properties. It is the material building block of power grids, electrical systems in buildings, and energy generators, both clean and dirty.[9] For this reason alone, global copper demand is forecast to increase rapidly, and no other mineral could effectively take its place.

In the transition to a clean energy future, the world will require as much copper in the next 25 years as was produced in the last five millennia.[10] To meet this demand and cap global warming at 1.5°C, global production of nearly every base metal (including copper, aluminum, magnesium, nickel, and lead) is expected to increase by 225%–250% in the next 30 years, according to the World Bank (see Exhibit 1: Historical and Projected Copper Production).[11] But as demand accelerates,[12] the mining industry's role in climate change threatens to grow at an even faster pace.[13] In 2012, the global metal sector consumed 52 exajoules (EJ) of energy,[14] accounting for 10% of global primary energy consumption. For reference, global home electricity demand in the same year was 18.4 EJ.[15] As high-grade mineral deposits become scarcer, the energy inputs to produce metals will increase exponentially.[16]

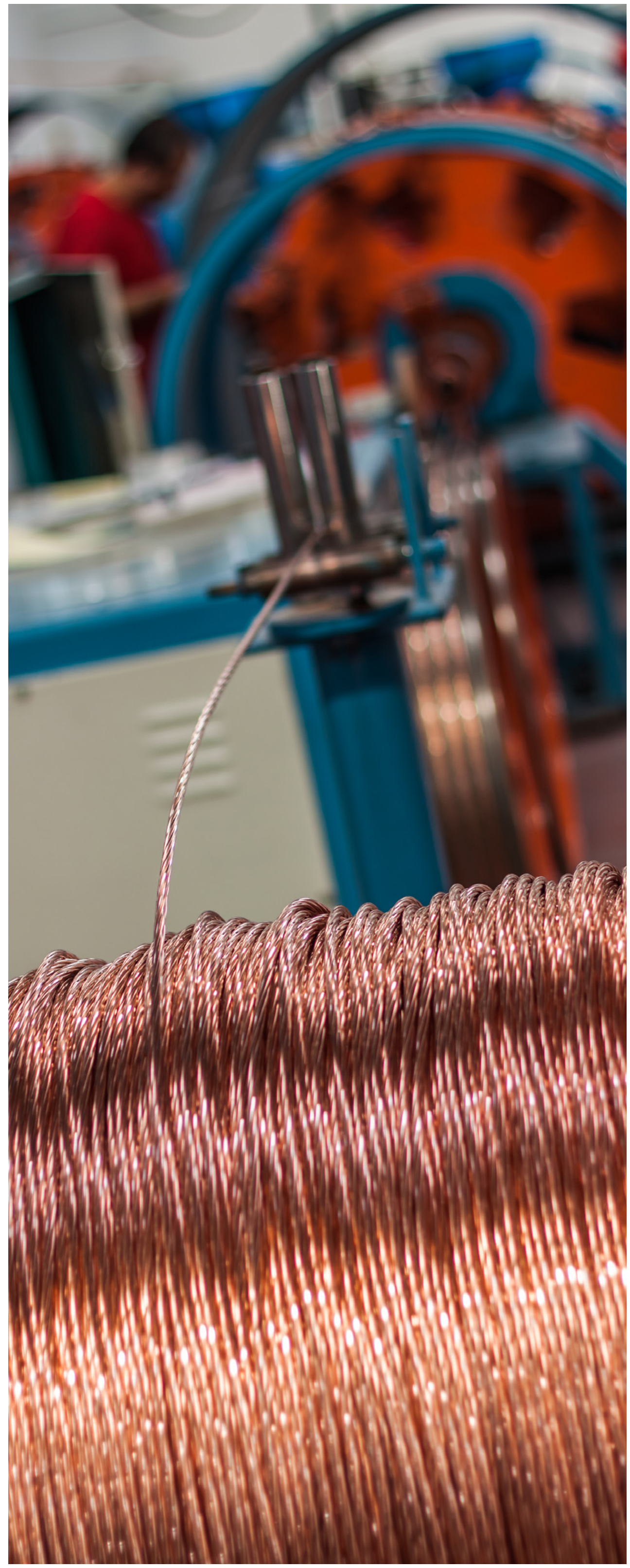
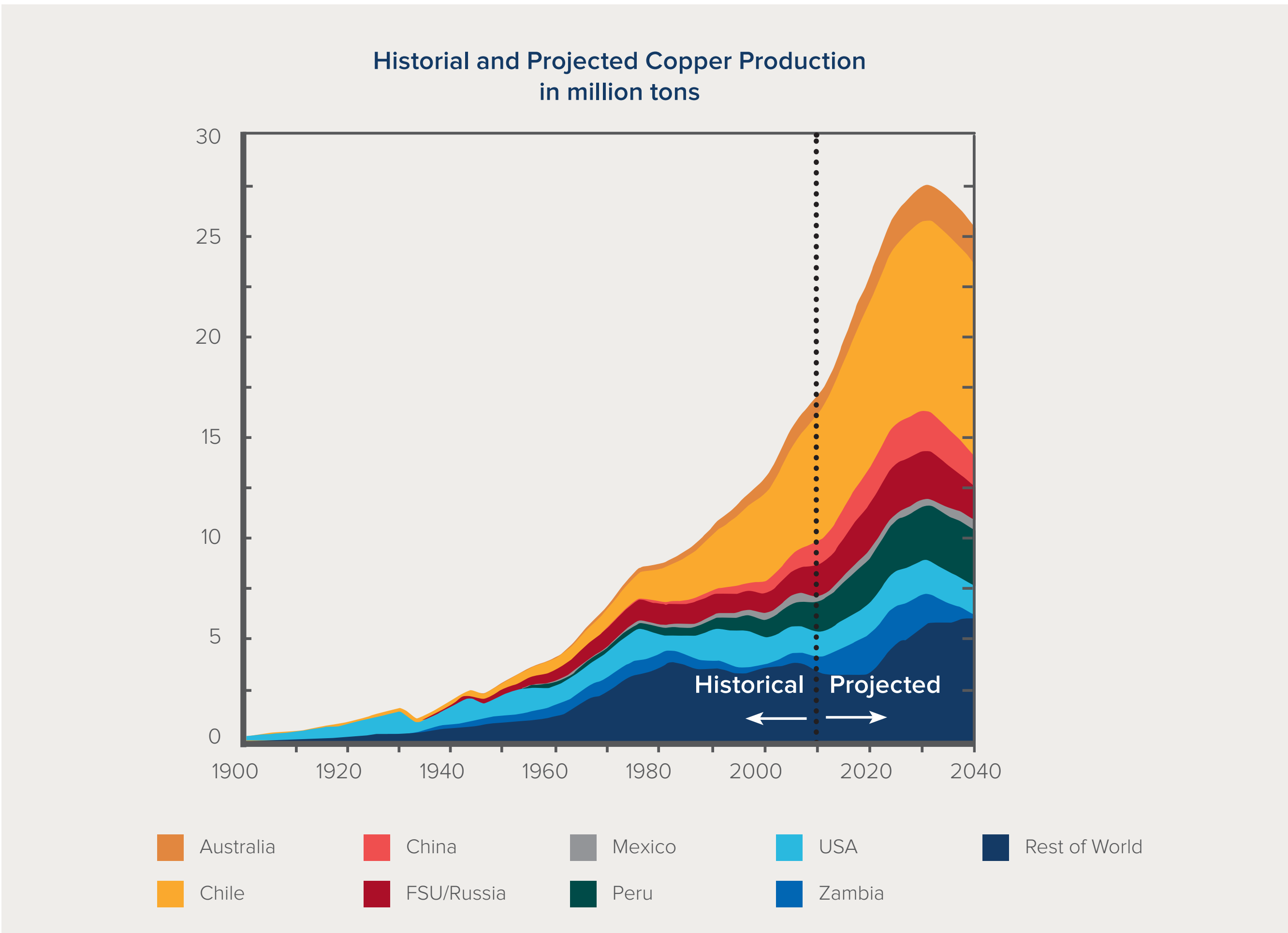


**EXHIBIT 1**

Historical and Projected Copper Production



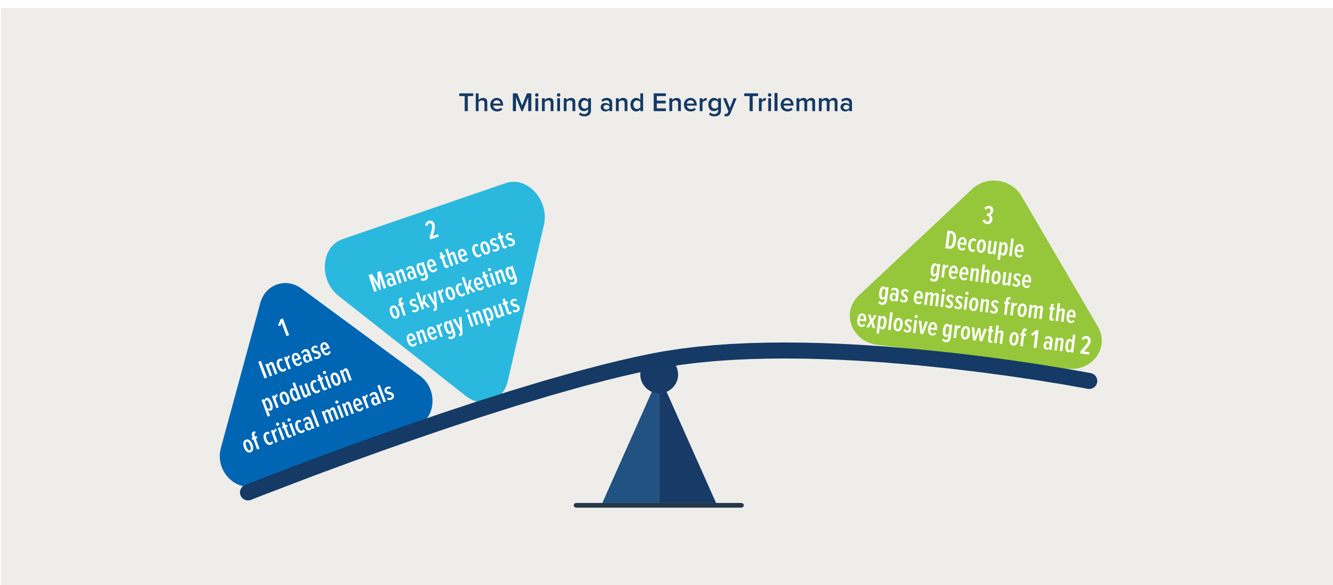

**Source:** Source: Northey et al. (2014)[17]

Capping global warming at 1.5°C requires that global emissions reach net zero by 2050, according to the United Nations Intergovernmental Panel on Climate Change.[18] A rapid and cost-effective clean energy transition is particularly important for the mining industry and its large energy footprint. This challenge puts metals producers in a position in which they must balance three priorities at once, each a challenge in its own right. In the next three decades, the sector needs to (1) increase production of critical minerals, (2) manage the costs of skyrocketing energy inputs, and (3) decouple greenhouse gas emissions from the explosive growth of (1) and (2). In other words, mining companies must strive to increase their material output while decreasing their carbon-based energy inputs (see Exhibit 2: The Mining and Energy Trilemma). Failing to meet either the first or second criteria would significantly slow the clean energy transition by constricting supply and increasing costs of critical minerals. Failing to meet the third goal threatens to undermine a low-carbon future by creating a world where the adoption of renewable technology incurs an enormous carbon debt—two steps forward but one step back.

Copper serves as a flagship mineral to illustrate the challenges and opportunities of decarbonizing the mining sector, with findings that transfer across a wide range of metals and processes. The first section of this report focuses on copper to illustrate the need for a new energy paradigm in the mining sector; the second section details how mines can begin the process of decoupling emissions from production growth using readily-available technology; and the third section of this report explores several case studies to show how mines can produce or procure 45% renewable electricity to increase profitability, decrease operating expenses (OpEx), and protect the health of employees, all while adding resilience to an industry that is too frequently ignored in conversations about a sustainable and climate-stabilized future.

**EXHIBIT 2**

The Mining and Energy Trilemma



## COPPER: A FLAGSHIP MINERAL

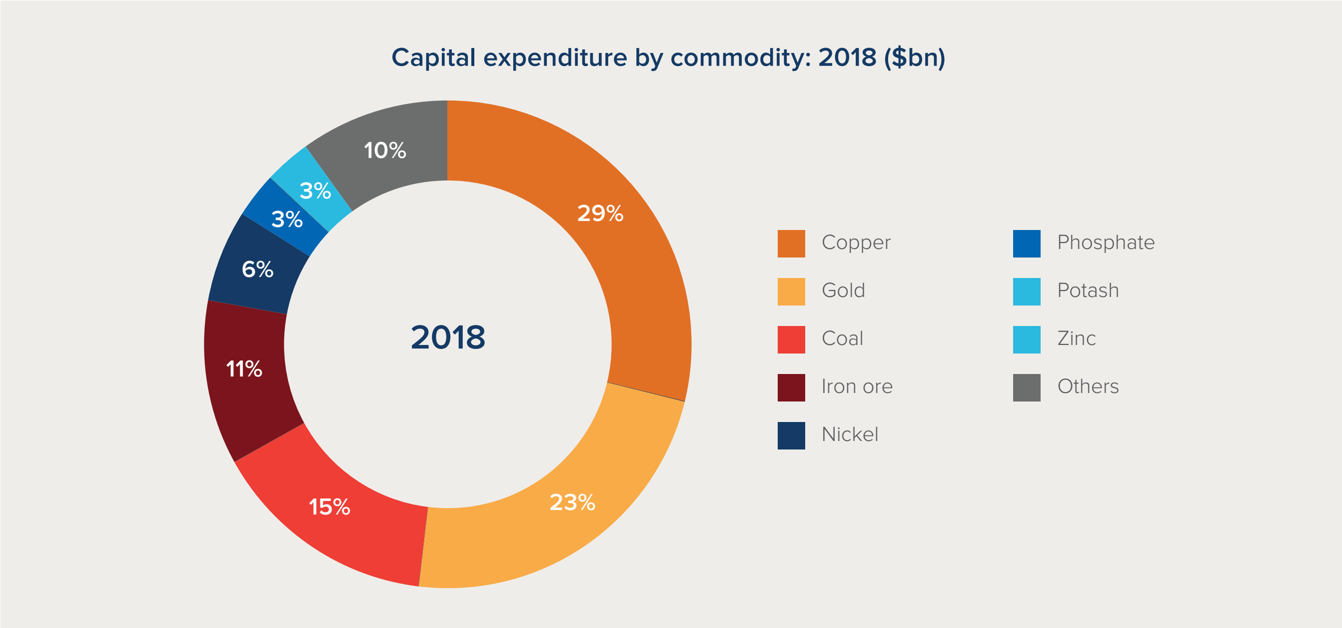
Copper is central to the global mining industry and our modern world. The anticipation of rising copper demand is shaping markets and driving investments, even as the mineral becomes progressively scarcer in the earth's crust. In 2018, the world's 40 largest mining firms spent $30 billion to develop new copper resources, more than any other mineral, including coal (see Exhibit 3: Capital Expenditure (CapEx) of Top 40 Mining Firms).[19] In the same year, 23% of revenue for the top 40 firms came from copper, roughly equal to the revenue share from coal but far ahead of all other minerals.[20]

But unlike coal, copper is essential to a clean energy future. Consider that a 3-megawatt (MW) wind turbine requires 4.7 tons (9,400 pounds) of copper,[22] or that electric vehicles require three times more copper than their fossil-based predecessors.[23] Copper also forms the foundation of more efficient 21st-century power grids, along with the wiring that electrifies buildings that previously used fossil fuels for heating and cooking. But growing demand—partly owing to booming renewable energy development[24]—is leading to near-term market shortages. Independent analyses from Citibank, Morgan Stanley, Goldman Sachs, and DBS Bank predict a copper supply deficit beginning sometime between 2019 and 2022,[25] and a report by Forbes from December 2018 revealed that total global copper stockpiles could only meet 12 days of production. While these shortages are driving increased recycling of scrap copper, only 17% of total production is met using recycled material.[26]

In light of future demand growth and present-day supply shortages, copper is arguably the flagship mineral of an industry in transition, where demand is increasing rapidly, scarcity threatens supply, and a renewable energy future depends upon minimizing the economic and environmental costs of production.

### EXHIBIT 3

CapEx of Top 40 Mining Firms




**Source:** PricewaterhouseCoopers (2019)[21]

# 1. RESOURCE SCARCITY AND MODERN MINING

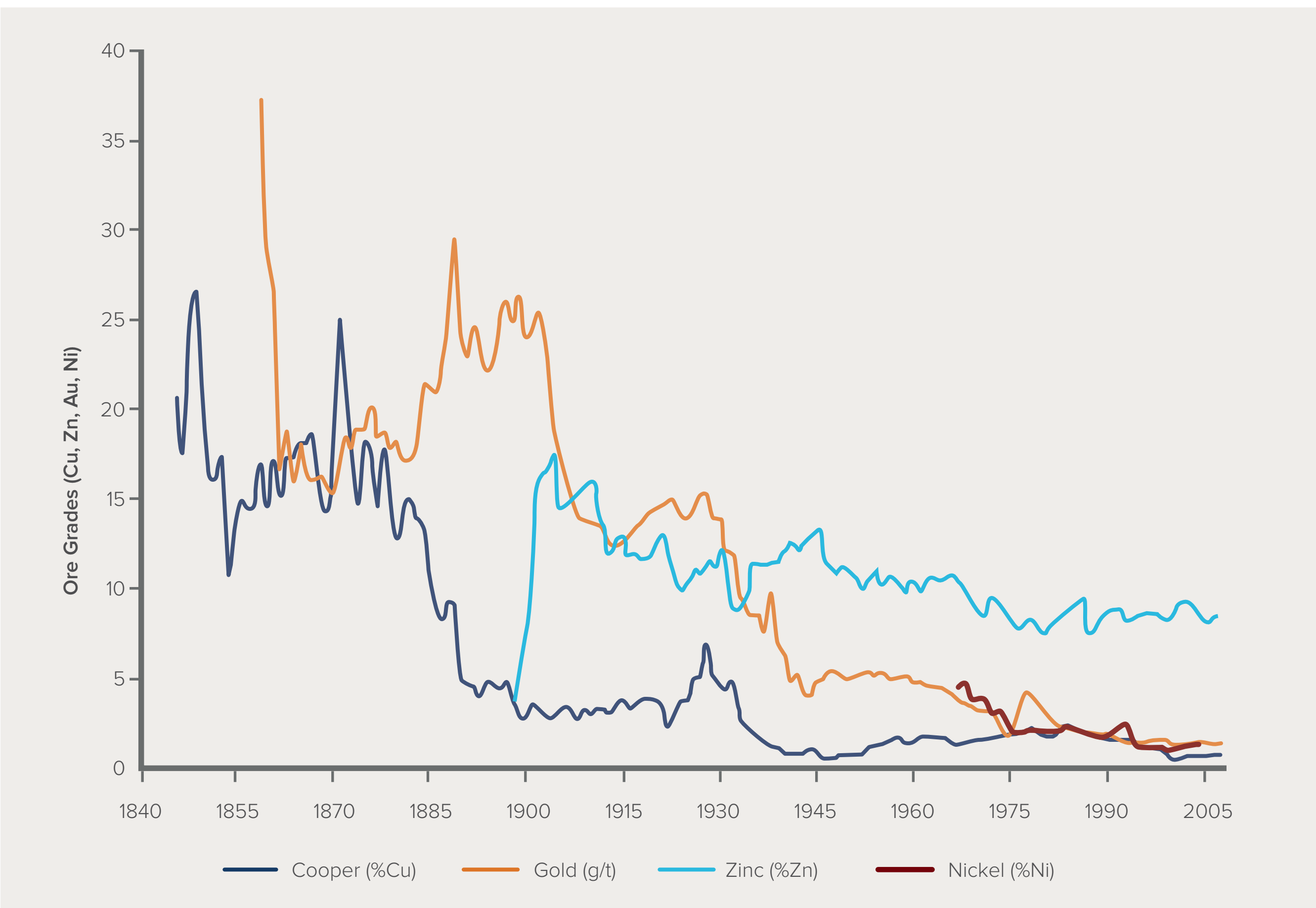
Once mined, minerals enter a global supply chain where customers around the world shop for the cheapest product available. In this business context, transnational mining companies compete to exploit the most economically efficient mineral deposits, where the lowest mining cost yields the highest profits. Because of this, mining firms pay close attention to geology but are mostly unconcerned with geography. Firms attempt to locate and develop sites with the highest density of valuable minerals. For this reason, mines are particularly concerned with ore grade, or the ratio of desirable metal to undesirable rock in a given area.

In the past century, high-grade ore deposits have declined rapidly, forcing mining firms to find new ways to exploit low-grade deposits (see Exhibit 4: Decline in Ore Grades of Copper, Gold, Zinc, Uranium, Nickel, Diamonds, and Silver). But to extract a given quantity of a mineral from a lower-grade deposit, miners must move more earth and process more ore, increasing the energy intensity of production.

In the copper industry, ore grades have declined rapidly over time. At the beginning of the 20th century, mines in Australia and the US extracted ore containing 2%–4% copper.[27] Today, the global average grade of

**EXHIBIT 4**

DECLINE IN ORE GRADES OF COPPER, GOLD, ZINC AND NICKEL




**Source:** Norgate and Jahanshahi (2010)[31] mined copper ore is 0.62%, with US and Australian averages at 0.34% and 0.63%, respectively.[28] Many mines are already producing metal from extremely low-grade ore, such as the Aitik mine in Sweden, with 0.21% copper by mass,[29] where the economic rationale for the copper extraction is driven by the value of other minerals contained in the same ore. The economic and environmental dynamics of copper mining will be shaped by this scarcity as progressively more capital and energy are required to produce the same amount of copper.[30]

### Glossary of Mining Terms

**Concentrate:** The resulting material once ore has undergone primary processing and waste removal.
Cradle-to-entry gate: The segment of the materials value chain that begins with mining and ends when a material arrives at the "factory gate."
**Extraction:** The process of removing ore from the earth (does not include processing).
**Ore:** Rock containing one or more economically valuable minerals.
**Ore grade:** The amount of a given metal (by mass) contained in an ore deposit.
**Mining:** See Extraction.
**Primary processing:** The initial processing that produces smelter-ready concentrate from mined ore.
**Refining:** The final step(s) to producing market-ready metal, usually following smelting.
**Reserve:** Economically viable minerals that have not been extracted.
**Smelting:** Applying heat to processed ore or concentrate to extract a metal.
**Stripping ratio:** The ratio of waste rock that must be handled and removed to extract a given amount of ore.
**Waste:** Undesirable rock that is removed during the mining and primary processing phases of mineral production.

## THE ENERGY-SCARCITY NEXUS

As demand for critical minerals drives production—and as production increases scarcity—a wide range of industry experts have warned of the "increasing ecological expenditure" (i.e. cost) of with future mineral development.[32] Alongside this ecological expenditure, costly investments in new energy infrastructure threaten the long-term viability of mine assets around the world.

For many minerals, including copper, declining ore grades will cause a ramp-up in energy demands that will transform value chains, creating a major obstacle to global decarbonization. These dynamics—and the dangers of climate change—pose a challenge to the strategic futures of mining firms themselves. In a 2018 speech, Simon Thompson, the chairman of Rio Tinto's board of directors, said that "perhaps the greatest long-term threat to Rio Tinto is if business, investors, consumers, and especially governments, collectively fail to take action on climate change."[33]

The nexus of resource scarcity and energy is rooted in the processes that transform rock into usable material. For copper, production occurs in four phases: mining, processing, smelting, and refining.[i] Mining usually involves blasting or drilling to remove large amounts of copper-bearing rock and waste. Processing involves crushing and grinding this rock—usually bearing 0.4%–1.0% copper—into a fine dust, which is then mixed with fluids and separated out to create copper concentrate, a slush of roughly 30% copper content. The concentrate is then smelted in furnaces that yield copper anodes (positively charged electrodes) of 99% purity. Lastly, the electrolysis process passes an electrical current through copper anodes suspended in an ion bath, which refines the copper into copper cathodes (negatively charged electrodes) of 99.99% purity and shaped in standardized shapes and weights, ready for use by industry.

[i] Recycled, or secondary, copper involves different processes. High-grade scrap can be re-melted without processing; lower-grade scrap is smelted and refined.

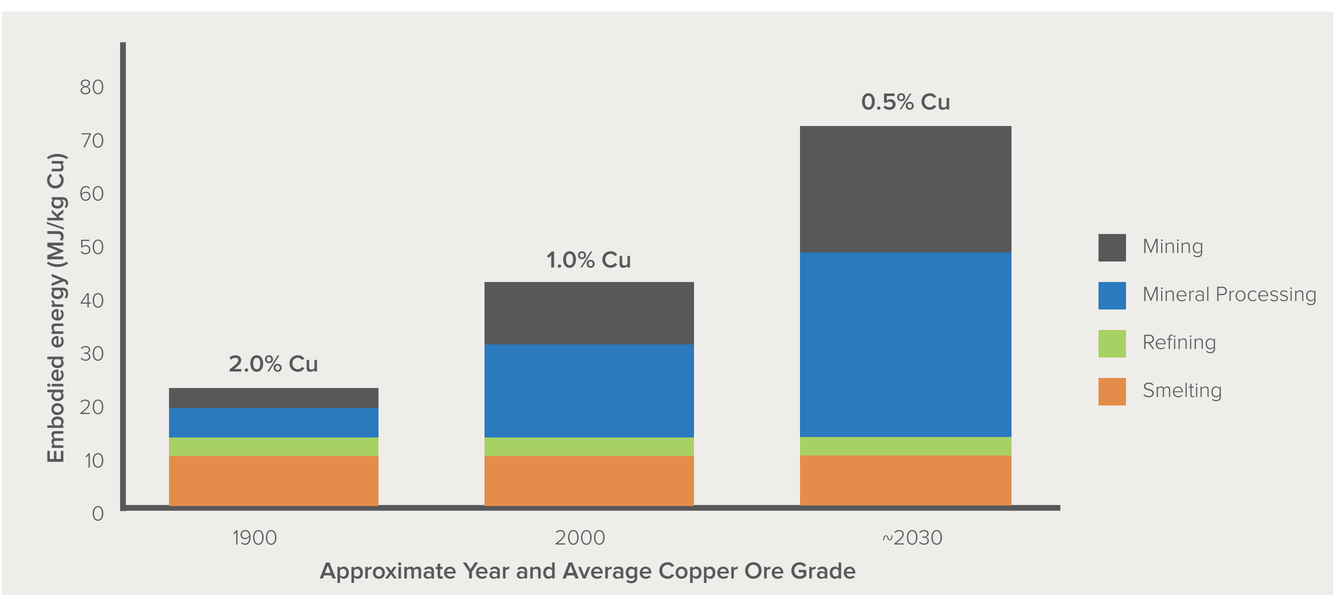
In the 20th century, mining operations spread their energy inputs relatively equally between these four stages. But as ore grade decreased, the amount of energy required for mining and processing grew rapidly (see Exhibit 5: Effect of Ore Grade on Stage-by-Stage Energy Consumption). Meanwhile, the energy inputs for smelting and refining remained fixed, as these latter phases involve already-processed copper concentrate.[34]

Energy inputs for mining have already risen substantially in the 21st century, but are certain to climb in future decades. The average copper ore grade is expected to decline to 0.2%–0.4% by mid-century;[36] extracting one kilogram of copper concentrate from these resources will likely require seven times more energy than present-day operations.[37]

Beyond contributing to climate change, the growing energy intensity of mining also poses a direct risk to the health and safety of miners. After decades of effort to ensure that mines are safe workplaces, fossil fuels threaten to reverse some of these gains by exposing miners to high quantities of airborne toxins. The primary hazard is diesel, which fuels a majority of underground mining equipment and produces carcinogenic fumes. Exhaust becomes concentrated in underground mine sites despite advanced ventilation systems. A 2017 study of more than 5,000 Western Australian miners found that a lifetime career working in an underground mine was associated with 38 additional lung cancer deaths per 1,000 miners.[38] For those miners working as underground diesel loaders, the additional lung cancer death rate was 79 deaths for every 1,000 miners, meaning that one in thirteen career-long employees die from lung cancer because of exposure to fossil fuels in the equipment they use. As mines move more earth to produce the same amount of metal, these deaths could increase if the industry does not find alternative ways to generate power.

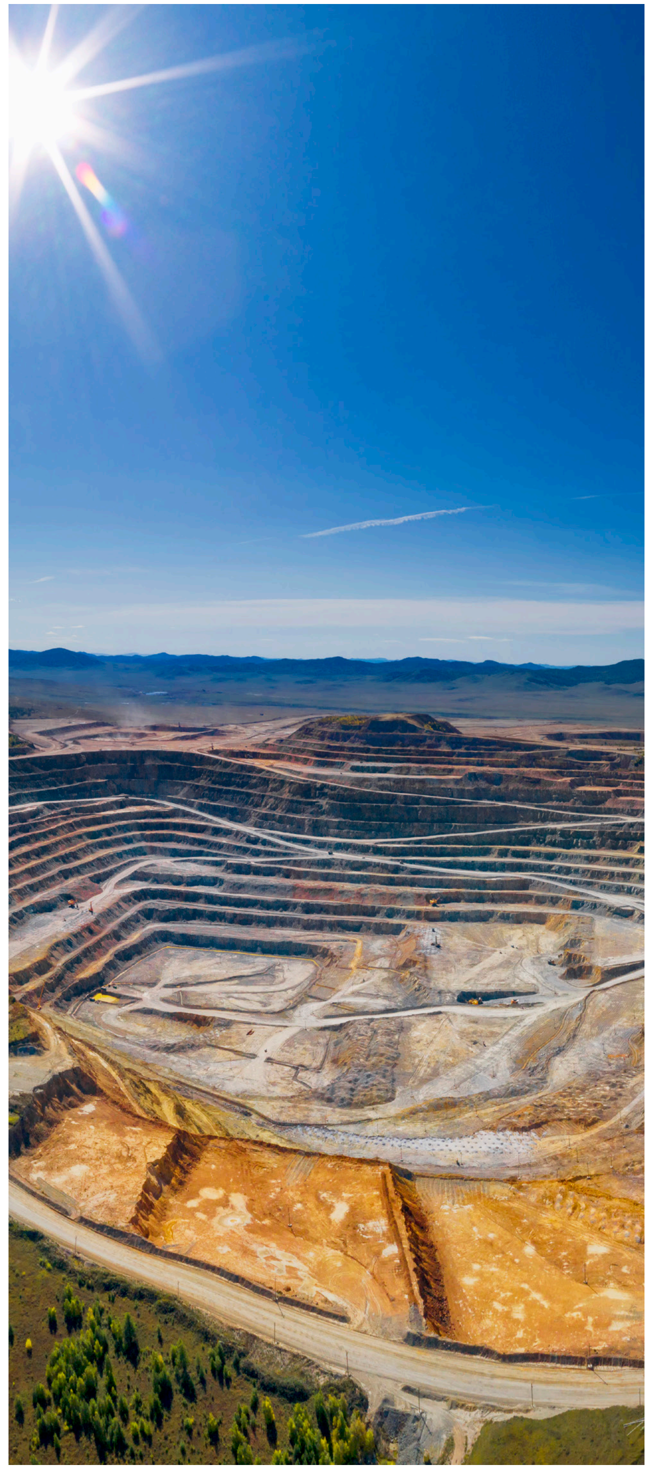
**EXHIBIT 5**

Effect of Ore Grade on Copper Production Energy Intensity




**Source:** Norgate and Rankin, (2000)[35], assumes 35% electrical generation efficiency

In sum, “business as usual” copper mining practices are at odds with a sustainable future. Copper production alone currently uses 0.3% of global energy demand. But experts at the Yale School of Forestry estimate that this figure could grow to 2.4% of global energy by mid-century.[39] Mines are already feeling the pressure of these growing energy inputs. Aaron Puna, the head of technical base metals at Anglo American, told the *Financial Times* that, “Compared to 100 years ago we are consuming . . . about ten times the energy [as before]. We can’t continue in this vein. We have to do something differently.”[40] A clean energy transition requires that the mining sector respond to this crisis by investing in cheap and renewable energy.



## A NEW ENERGY PARADIGM FOR MINES

At a time when global manufacturers in most industries are reducing their energy intensity, metals producers are moving in the opposite direction. This will lead to growing energy consumption in both absolute and relative terms, implying that energy use will rise disproportionally to meet growing demand and increasing scarcity. Securing profitability, managing costs, and facilitating a clean energy transition requires that mines pursue a new energy paradigm. In short, the mining sector must *decouple* production and profitability from carbon-based fuel consumption, growing the former whilst decreasing the latter.

The scale of this challenge is significant, but there is every reason to believe that decoupling mineral production is possible. One emerging trend is particularly encouraging: the ratio of electric demand relative to fuel energy is increasing. In other words, the industry is becoming more electricity-driven and less reliant upon carbon-based fuels. This transition can be met with readily deployable and scalable renewable technologies.

# 2. A PATHWAY APPROACH FOR DECARBONIZING MINE OPERATIONS

The prospect of rising energy costs places a particular set of pressures on industries like copper. The price of metals is volatile; during price drops, mines must decide whether to produce at a potential loss or pause operations until the market rebounds. OpEx inputs such as energy determine how much "cushion" a producer has during market downturns—if a mine can maintain low OpEx, then it will fare better when prices dip. By contrast, high OpEx becomes a major liability for mine assets by reducing the clearance between production costs and market price. Minimizing these costs serves as an insurance policy, safeguarding producers during market downturns and maximizing returns. As energy inputs soar, the market may become differentiated between those producers that secure low-cost energy and those that do not.

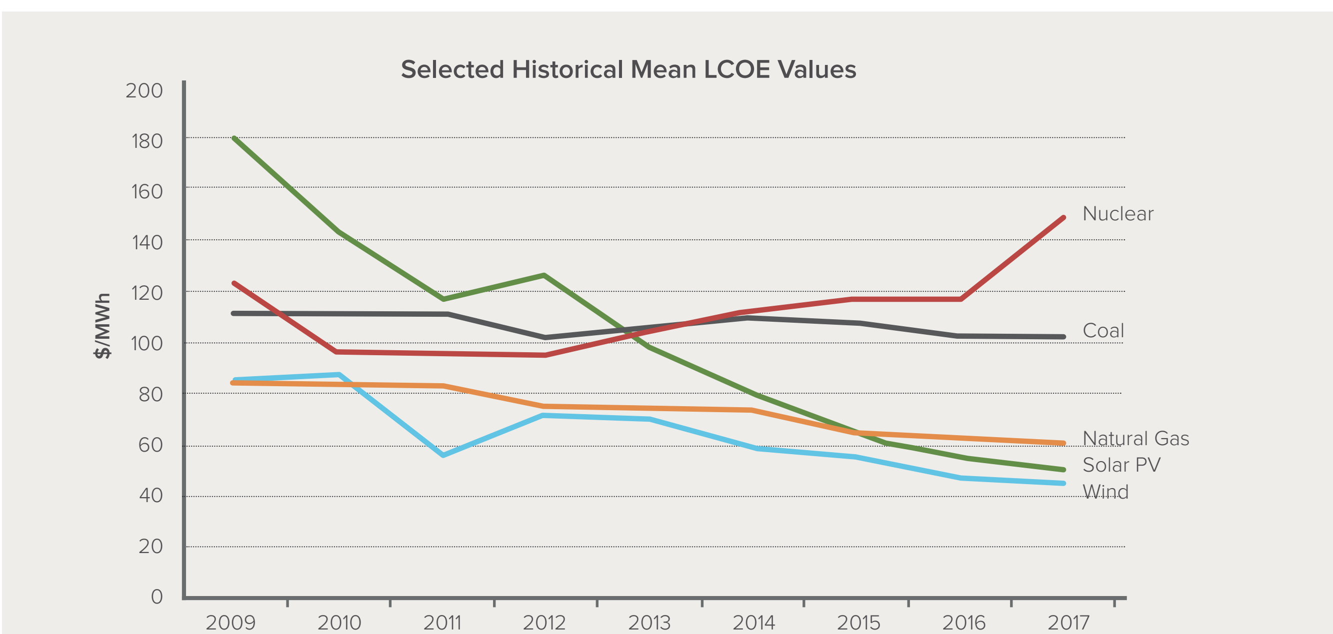
According to the International Energy Agency, the cost of fossil-based fuels is forecast to climb or, at best, remain stable in the next three decades.[41] Meanwhile, the cost of low-carbon technology is expected to continue to fall. This trend has been particularly pronounced for solar photovoltaic (PV) technology: the levelized (i.e., lifetime average) costs of solar electricity fell 88% from 2009–2018; a further 40% decline is expected by 2030. The cost of wind energy fell by 69% over the same period.[42]

Solar and wind technology have now matched or overtaken even the cheapest fossil-based power plants in a wide range of resource geographies. Whereas these technologies were previously cost-competitive only with subsidies, they presently offer the lowest-cost electricity of any energy technology (see Exhibit 6: Levelized Cost of Energy Comparison). Furthermore, renewable energy systems do not introduce reliability risks to grid connected systems.

It seems increasingly likely that the future of the mining industry will be driven by firms that are able to rapidly adopt lower-cost renewable energy technology, thereby gaining a competitive advantage over

**EXHIBIT 6**

LEVELIZED COST OF ELECTRICITY COMPARISON




**Source:** Lazard(2018)[44]

producers whose rising energy bills threaten their near-term viability. Without cheap and clean energy, some proportion of the world's proven and probable reserves will likely become "stranded assets" in the decades to come.[43]

## THE RENEWABLE ENERGY VALUE PROPOSITION

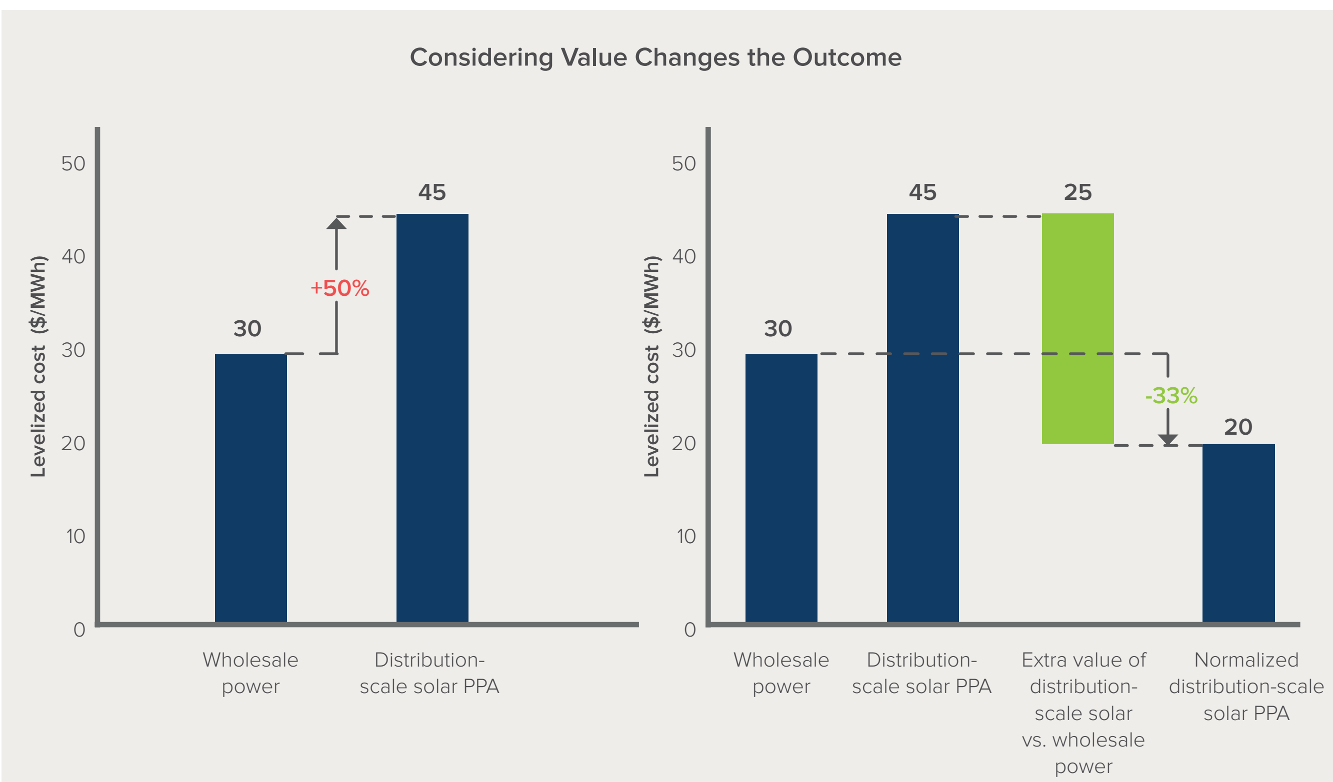
It is a common misconception that nonhydropower renewable technologies are limited to small and high-risk installations. However, large-scale, low-carbon electricity grids are online and generating in places where customers demand 100% reliability. In the past two years, the state of South Australia—more than twice the size of California—met 47% of its electricity needs with wind and solar, serving 2 million customers. On the other side of the planet, the US states of Iowa, Kansas, Oklahoma, and South Dakota met over 30% of their total electricity demand with wind power, serving 11 million Americans.[45]

By comparison, integrating renewable energy into mining operations is a much less complex undertaking in terms of capacity and distribution needs. Mines are highly centralized compared to utility districts, requiring relatively little transmission infrastructure. And with zero variable operating costs, high reliability, and the capacity to generate energy after mine closure, renewable energy technology offers mining firms a value proposition that reduces risk, minimizes costs, and decouples production from emissions.

RMI has studied how the cost of renewable energy fails to fully capture its value.[46] Often, the stated cost per unit of electricity omits additional benefits and avoided charges. In an analysis from 2018, RMI examined how

**EXHIBIT 7**

COSTS VERSUS VALUE OF DISTRIBUTION-SCALE SOLAR




**Source:** RMI (2018)[47]

net present value (NPV) and internal rate of return (IRR), rather than levelized cost of electricity (LCOE), provide a more robust and accurate reflection of the renewable energy value proposition (see Exhibit 7: Costs Versus Value of Distribution-Scale Solar).

Our results found that the value proposition of renewable energy far exceeds the "price parity" suggested by cost for a large number of reasons. Mines that invest heavily in renewable energy stand to gain the following benefits:

- Improve cash position in the face of market downturns by minimizing per-unit cash costs
- Improve work conditions and employee health by reducing toxic emissions
- Reduce risk profile by limiting exposure to increasing fuel prices
- Gain political capital with governments seeking to meet national climate goals as outlined in the Paris Agreement or in regional renewable portfolio standards
- Create energy infrastructure that will continue to hold value beyond the expected mine lifetime and generate revenue after mine closure
- Improve livelihoods in rural communities by generating reliable and low-cost electricity while reducing air pollution
- Increase resilience to carbon pricing or other emissions-reduction policies
- Reduce transmission and generation costs

Many mining firms are already taking advantage of these value propositions. Rio Tinto, the world's second-largest mining company by revenue, now sources 71% of its electricity from renewables. Since 2008, the firm has cut the emissions intensity of its production by 29%, outperforming its own emissions reduction target of 24%.[48] But Rio Tinto is an exceptional outlier and likely the only major mining firm to have initiated a portfolio-wide decoupling process. Hardly any other firms exceed even 10% renewable energy, according to a 2018 analysis by RMI.[49] Rio Tinto is positioning itself to benefit from an already-strong value proposition, knowing that the return on its investment will continue to grow.

At the asset level, large-scale decarbonization efforts are already operating or commissioned at a few pioneering mines around the world.

- The DeGrussa Copper-Gold Mine in Western Australia, with an average energy demand of 11 MW, commissioned a 10.6 MW solar array with 4 MW of battery storage system, serving a majority of daytime energy consumption.
- In Ontario, Canada, the Borden Lake gold mine will begin production in late 2019 using all-electric machinery—no internal combustion engines will operate belowground. Because 93% of Ontario's electricity is generated from low-carbon sources,[50] the Borden Lake project will become one of the lowest-carbon mines in the world.[51] The lack of fossil fuels also decreases the need for mine ventilation and provides a healthier environment for mine employees. The mine will use 40 metric ton Sandvik haul trucks solely powered by batteries to transport ore and waste rock.
- In June 2019, the Agnew Gold Mine announced plans for a renewable microgrid in Western Australia, costing AUD$111.6M (US$77.54M). Once completed in 2020, 55%-60% of the mine's energy will be powered by a combination of solar, wind, and storage, with a 16 MW natural gas station providing the remainder of the mine's electricity. In a press release, the executive vice-president of the mine's parent company, Gold Fields Australia, said that the "microgrid project reflects the company's strategic objective to strengthen energy security, optimize energy costs, and reduce its carbon footprint."[52]
- The Zaldívar copper mine in Chile will operate using 100% renewable electricity beginning in July 2020. Owned by Barrick Gold and Antofagasta, the mine will rely on a mix of solar, wind, and hydroelectric power.[53]

While operations like these harness renewable technology in service of long-term strategic goals, the majority of the mining industry continues to leave options on the table from an economic and environmental standpoint. RMI's Renewable Resources at Mines tracker shows that most mine assets either forego renewable energy entirely or opt for small-scale installations that underdeliver on price and performance by failing to capture economies of scale.[54]

## BARRIERS TO RENEWABLE ENERGY ADOPTION

The tendency of mining firms to leave options on the table with respect to renewable technology is a key obstacle to industry-wide progress. The most important barriers that prevent mining firms from adopting ambitious decarbonization plans are (1) market failures, (2) structural barriers, (3) organizational barriers, and (4) behavioral barriers and information asymmetry.

**Market failures** may constitute the most significant barrier to renewable energy adoption. Mines that emit carbon dioxide and other airborne pollutants do not bear the cost of these impacts upon livelihoods and the environment. Jurisdictions that have adopted carbon pricing are attempting to internalize these costs to correct this market failure, but the prices levied on emissions are usually too low to fully capture economists' best estimates of the damage they cause.

**Structural barriers** emerge when the nature of mining technology or commodities markets complicates renewable energy development. This is most apparent when a mining firm opts to minimize near-term costs by using fossil energy, rather than invest in renewable technology that provides better returns over the project lifetime. When relying on fossil energy, most mines will source electricity from local utilities or build diesel generators. These systems have high variable costs but relatively low capital costs, whereas renewable energy investments usually have payback periods of 3–10 years.

The high price tag of renewables is a significant hurdle to their adoption. Producers look to shield themselves against volatile commodities markets; because firms cannot accurately predict future metals prices, shareholders have an added incentive to minimize return-on-investment periods. This short-term bias makes the value proposition of renewables less palatable. Fortunately, financing arrangements or power purchase agreements (PPAs) can mitigate the capital burden of renewable energy by recruiting developers to shoulder the upfront costs of building new infrastructure (see Financing Renewable Infrastructure, below).

Another structural barrier to renewables integration owes to the long life of existing assets on mine sites. Firms may reject cost-saving measures that require prematurely retiring fossil fuel-based machinery, even if the value proposition of low-carbon technology justifies the accelerated phase-out of existing assets. This technical lock-in has dogged similar efforts to decarbonize the maritime shipping industry and the power generation sector, where cargo ships and coal plants are expected to spend decades in service.[55] Firms with durable carbon-based assets will often eschew renewable alternatives, even when the sum of existing variable costs exceeds the net present costs of a fossil-free replacement.

**Organizational barriers** also play a role in reducing renewable energy uptake. While executives or board members might appreciate the renewable energy value proposition, operations personnel may be skeptical of a change that they see as threatening a short-term disruption in energy supply. This barrier may restrict the ambition of executives to pursue energy transitions. In addition, mines have developed decades of expertise using diesel-powered machines and grid-connected electrical systems. This creates a bias toward those technologies that are most familiar to employees and decision makers.

**Behavioral barriers** can drive irrational decision-making and lead to suboptimal outcomes. This is most apparent when a mining firm chooses to reduce near-term costs despite an alternative investment that provides better returns over the project lifetime. Because renewable energy involves high capital costs, many firms default to using fossil-based energy. Most mines will source their electricity from local utilities or build diesel generators to begin operations while grid transmission lines are installed. These systems have high operating costs but relatively low up-front investments compared with renewables. This short-term outlook—often compounded by status quo bias—can lead to economically irrational decision-making.

In response to this barrier, renewable energy financial mechanisms have evolved to reduce these upfront costs. Debt financing, for example, reduces the net present costs of clean energy investment and corrects this market failure. PPAs offer another common market mechanism to limit CapEx in renewable energy sourcing. In a PPA, a mining firm contracts renewable energy from a developer and provider. This offers certainty to the renewable energy developer that their generated power will find a buyer while providing mines with access to clean, low-cost power and a predetermined price schedule.

Lastly, **information asymmetry** may delay renewable energy adoption. Renewable technology is poorly understood outside the energy industry; what's more, finding information and expertise on low-carbon power generation requires time and resources. Some industry actors may feel that renewable energy represents a risky gamble on unproven technology. Known as "sociotechnical lock-in" among renewable energy specialists, this fear of lesser-known technologies interferes with rational decision-making, often leading to economically unfavorable outcomes. This is well illustrated by the slow uptake of renewable energy by mining firms despite the obvious value proposition.

In spite of these barriers, economic and environmental pressures to decarbonize are growing. This is particularly true of investors and bulk metal consumers who are taking steps to align their portfolios with a 1.5°C climate-stabilized future. For instance, the capital- and energy-intensive maritime shipping industry has begun to adopt emissions-based investor protocols.[56] Major consumers are also showing a growing preference for sustainable minerals; Apple is partnering with global aluminum giants Rio Tinto and Alcoa to back the development of low-carbon smelting technology.[57] As consumer awareness increases, certain firms have shown a willingness to pay for sustainably produced metals as they reduce the carbon intensity of their products. This transition may soon split uniform commodity markets into low-carbon metals and high-carbon metals, mirroring how Fairtrade coffee and chocolate or Forest Stewardship Council timber created separate markets for those respective commodities.

The urgency of climate change and the opportunities of clean energy should lead metals producers to take swift action to overcome the inertia of carbon-based energy inputs and reduce their greenhouse gas emissions. In doing so, firms decrease risk, improve market resilience, and align their operations with global emissions targets and shifting consumer demand.

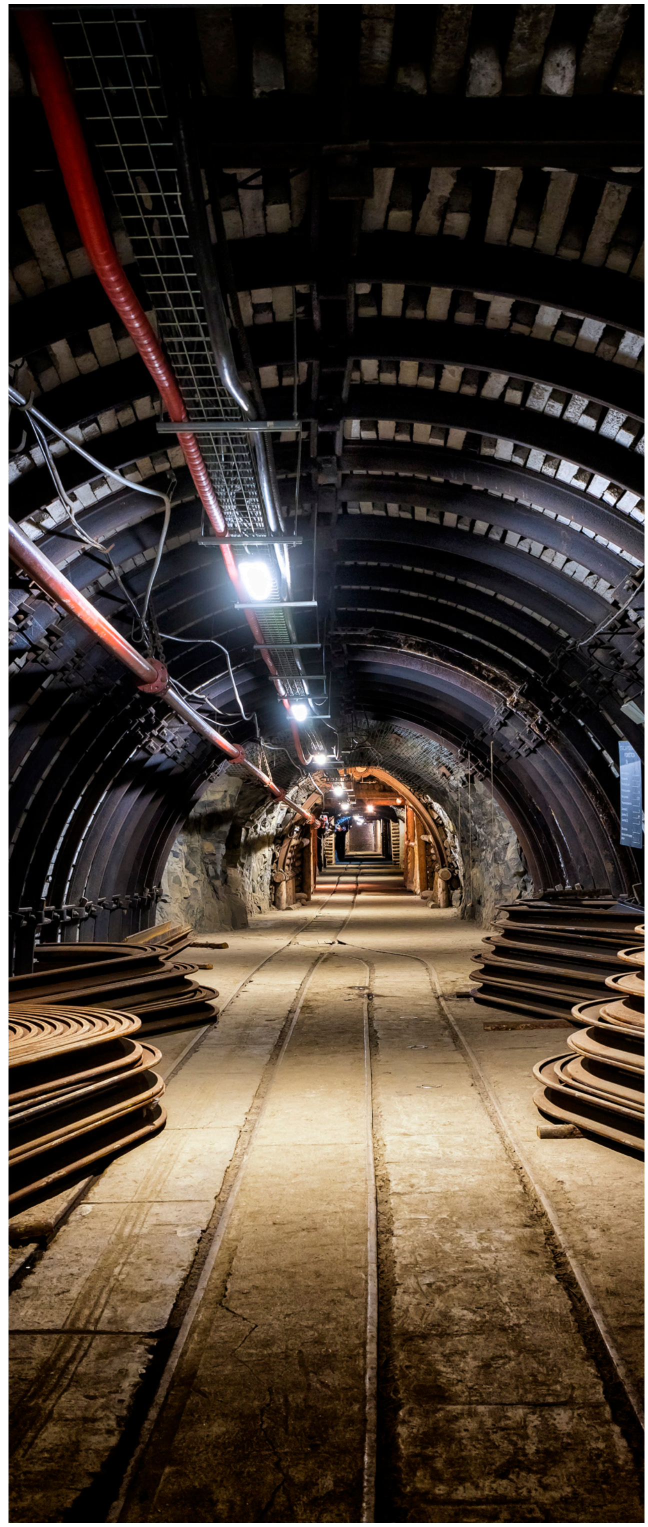
# 3. A FIRST STEP TO DECARBONIZATION

While all mines are unique, advances in renewable energy technology have made site-to-site variation less important over time. RMI has designed a one-size-fits-most approach to decarbonizing mines, trialed across three continents with industry-standard renewable energy modeling techniques.

The approach outlined here is a first step for industry players. As such, it is tailored to incorporate only readily available and low-risk technology. The model used here also employs conservative cost estimates for renewable energy. Despite this conservatism, it is important to note that the cost of low-carbon energy systems continues to fall, with new technologies like storage and hydrogen becoming cost-competitive in a greater range of applications (see Achieving Net-Zero Emissions, below).

RMI modeled a decarbonization pathway for twenty-five real-world mine sites from five mineral-rich countries: Chile, Peru, the United States (Arizona), Australia (Western Australia), and Mexico. Cumulatively, these countries represent a majority of global copper production. These sites were selected in part for their abundant renewable energy resources, and it is a fortunate coincidence of geography that copper-rich regions tend to be located in low-latitudes with plentiful sunshine.

Of course, not all mines can achieve outstanding economic performance by decarbonizing their electricity supply. But those mine assets without access to cheap and clean energy will likely find themselves at a competitive disadvantage in the coming decades, as energy accounts for an increasingly large share of per-unit production costs for critical minerals like copper. In this new paradigm, mines with access to cheap, clean, and abundant energy will outperform those assets that continue to rely on expensive and dirty energy.



## A "ONE SIZE FITS MOST" APPROACH

In each of the five countries examined, the average mine was able to achieve greater than 45% electricity decarbonization at a significantly lower cost than with local grid energy, suggesting a useful benchmark for the industry given current renewable energy prices. The modeled pathway also met or exceeded industry-standard key performance indicators, demonstrating that investments in low-carbon technology provide the same economic returns that mining firms expect for any major business decision.

### Methodology

The decarbonization model examined the net present cost and internal rate of return of partially decarbonizing a mine's electricity supply. The analysis used real-world mine sites but modeled a generic, mid-size mine with an average electricity demand of 50 MW. Technical modeling was completed using HOMER (Hybrid Optimization of Multiple Energy Resources) microgrid modeling software, generating hundreds of thousands of simulations across all scenarios. The cash flow of each energy project was analyzed relative to a counterfactual with 100% grid-supplied electricity. Industrial energy rates were compared with CapEx and OpEx for renewable technology deployment. Each scenario incorporated NASA or National Renewable Energy Laboratory solar irradiance data for the particular geography. In all cases, the modeled investment employed 50% debt financing with 6% interest and a 7.5% discount rate. Cases in the United States modeled a tax equity investor at 40%, with an additional 10% in debt financing. For all cases, the analyzed cash flows represent pre-tax amounts and do not account for local renewable incentives. The LCOE for the modeled solar installations was conservative, ranging from \$35-\$45 per megawatt-hour (MWh); by comparison, a recent PPA in Los Angeles was priced below \$20 per MWh.[58] For more details, see Methodology in the Appendix.

The success of our one-size-fits-most approach was made possible by low-cost solar energy. By installing large-scale solar arrays, most mines in sunny places can easily meet 35% of total electricity demand at price points that far outcompete grid electricity. But for geographies with cheaper electricity or more limited solar resources, electricity decarbonization of 45% requires hybrid systems and a portfolio approach to renewable energy procurement.

The decarbonization pathway that emerged from this analysis resembles a prix fixe dinner menu, with a set "main course" of large-scale solar and a "dessert menu" of technology or policy options, any one of which can carry a mine asset over the finish line to reach 45% decarbonization.

The "dessert menu" includes the following options:

- **Wind power** (e.g., the 115 MW El Arrayán wind farm at the Los Pelambres copper mine in Chile[59])
- **Lithium-ion battery storage** (e.g., the 13 MW/4 MWh storage facility at the Agnew Gold Mine, Western Australia[60])
- **Pumped-hydro storage** (e.g., the 250 MW project currently under development at the Kanmantoo copper mine in Adelaide Hills, South Australia[61])
- **Concentrated solar power** (e.g., the US\$2.3 billion Cerro Dominador power plant in Chile, which includes 110 MW of concentrated solar power thermal storage[62])
- **Excess generation buyback programs** (e.g., common in utility districts across the world)

Matched with an appropriate geography and paired with solar, these systems achieve deep emissions cuts that provide long-term strategic advantages to mines. RMI conducted a standardized to test how one of these "dessert" options influenced the economics of deep decarbonization (see Exhibit 8: Decarbonization of Solar Only vs. Portfolio Sites).

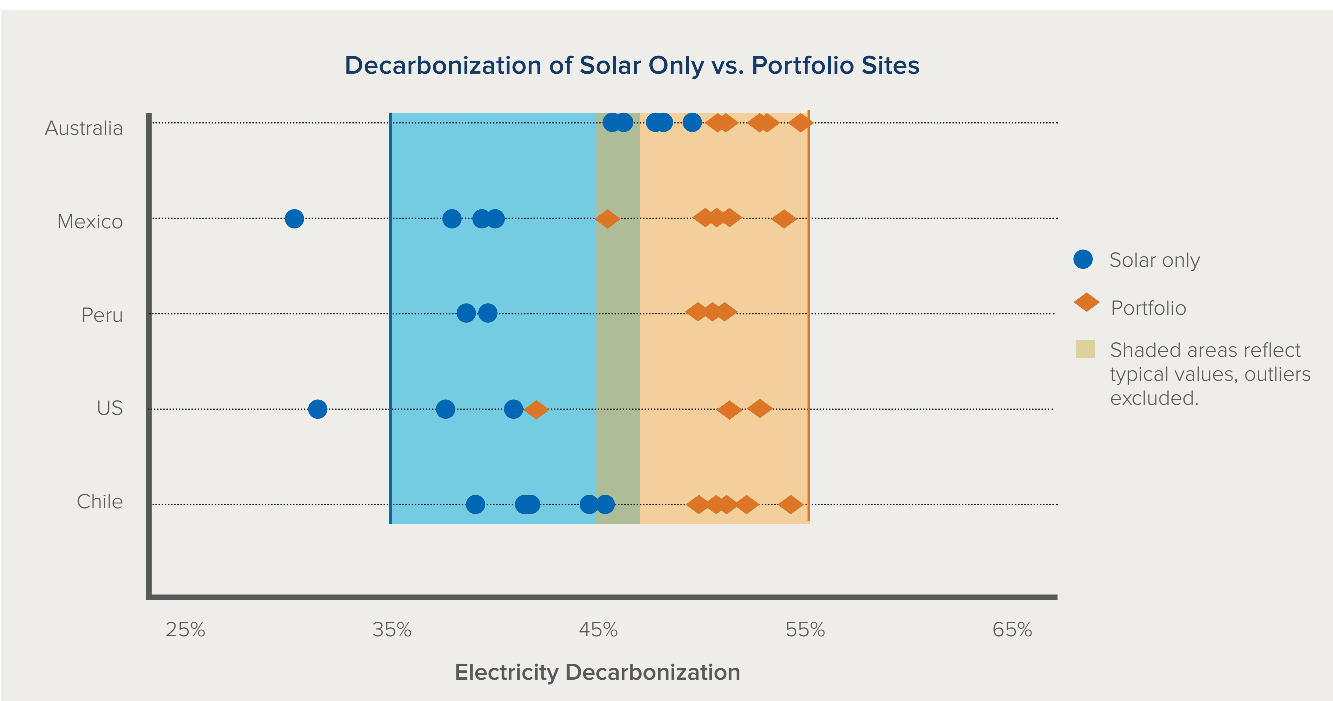
The analysis showed that solar energy without optimization supplied 37% or more of the electricity demand for a majority of modeled mine sites while yielding strong financial returns. But with the addition of other renewable technologies or a utility buyback program at two-thirds of the electricity rate, renewable electricity supply increased to 45% or more. On average, this further increase in decarbonization maintained a constant IRR, while increasing NPV by 21.5% and reducing the payback period to 6 years. These figures identify missed opportunities across the mining industry and options left on the table by investors. Many of the mines operating in the assessed regions are declining to capitalize on strategic investments worth tens of millions of US dollars in NPV. The consequences of this inaction are reduced profitability and resilience, and a more dangerous climatic future.

## GROUNDING THE ANALYSIS

The analysis from these five countries relies on generic inputs, including conservative, geographically agnostic solar pricing, and publicly available energy data. To validate these findings, the model's solar-only results were compared with the outcomes of in-depth studies that RMI has performed with industry partners in four of the five countries examined above. In each of these cases, RMI assessed the renewable energy potential for a mine site using specific inputs, such as actual electrical load profiles, local taxes and incentives, interconnection costs, and available land for installing new energy infrastructure. Using

**EXHIBIT 8**

Decarbonization of Solar Only vs. Portfolio Sites

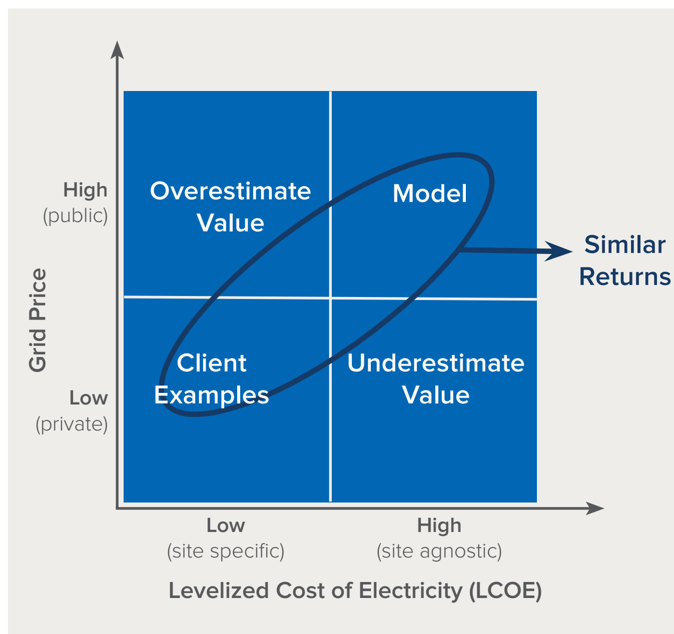



**Source:** RMI Analysis

site-specific data and bullish cost trends in solar markets, the built cost of systems that RMI modeled return lower LCOE values than those modeled in this report. But they also use lower electricity prices, as industrial power customers often receive electricity at discounted rates that are not publicly available. These discrepancies between in-depth case studies and the generic model effectively balance each other, such that the difference between LCOE and electricity prices are roughly consistent across both datasets. The figure below illustrates how, despite these differences, the site-specific analyses yield similar returns to the generalized model.

**EXHIBIT 9**

Comparison Between LOCE and Grid Price




**Source:** RMI Analysis

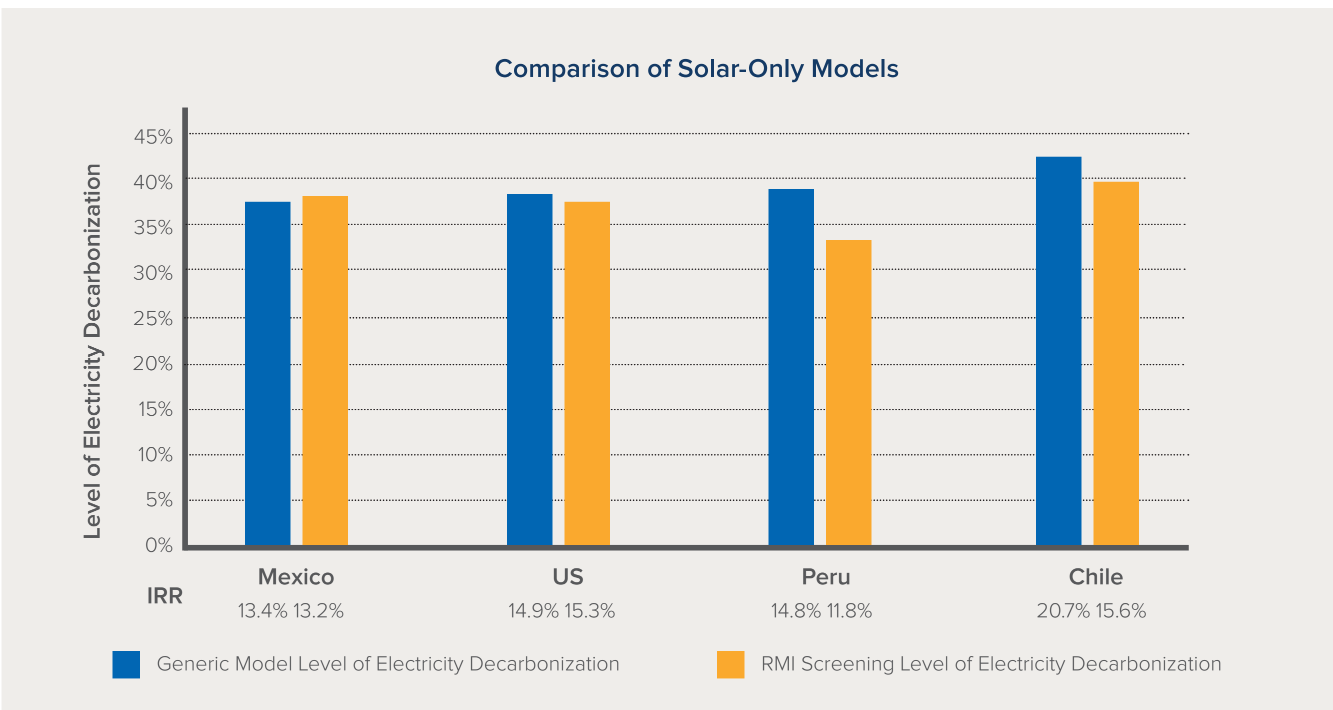
To further validate the model above, the renewable energy systems modeled in RMI studies were increased in size, holding all other variables constant, until the percentage of electric load met matched the level of electricity decarbonization analyzed above. In this validation step, the IRRs were compared between high-level modeled results and detailed RMI pre-screening studies. The results of this validation are presented in Exhibit 10: Validation of Renewable Electricity Model.

In almost all cases, the results of the model converge with the in-depth case studies undertaken by RMI using detailed site-specific information. The lower returns in Peru and Chile are explained by a greater price difference between the cost of solar electricity and grid power, as real-world industrial customers receive significant discounts on wholesale electricity purchases. Despite these differences, the results are within five percentage points and all cases clear a hurdle rate of 10% IRR. The consistency of these datasets adds further confirmatory evidence that the publicly available data employed in the general model returns representative real-world results at industrial sites.

Taken as a whole, this analysis suggests that 45% decarbonization is an appropriate benchmark in a wide range of geographies for most mining firms to align their business goals with the global effort to halt climate change and protect the health of communities.

**EXHIBIT 10**

Validation of Renewable Electricity Model



## BEYOND NPV AND IRR

Mining companies operate in a complex economic ecosystem. Key performance indicators such as NPV and IRR rarely provide a comprehensive overview of the impact of investment decisions. To justify the large capital costs of renewable energy, the low-carbon value proposition must also make sense in the broader macroeconomic landscape of metals production. RMI's research and real-world experience demonstrate that renewables integration on mine sites performs well across traditional key performance indicators, but renewable energy confers numerous benefits that traditional metrics fail to capture. Most notably, renewable energy in mining (1) **reduces operational costs per unit of production,** (2) **increases mine resilience to market swings,** (3) **limits exposure to fluctuating fuel prices and carbon taxes,** and (4) **generates an asset that retains value in the event of mine closure.** These four benefits are detailed below.

1. Traditional energy infrastructure requires continued payments of electricity and fuel bills—an expensive variable operating cost. Renewable infrastructure, by contrast, has much lower (or zero) variable operating costs without compromising on power reliability (for grid-connected systems). Maintenance expenses are also small: annual operation and maintenance (O&M) costs for wind turbines are fewer than 3% of purchase and installation costs.[63] For solar, the same O&M costs are less than 1% of CapEx.[64] These low variable expenses significantly reduce the cash cost per unit of metal produced.

2. Low variable costs also add to mine resilience during commodity market downturns, cushioning marginal investments. When metal prices fall, producers with low energy costs will produce below market price, while mines with high energy costs may fail to do the same. This added resilience safeguards assets' profitability and protects employees' livelihoods during short-term economic turmoil.

3. Critically, renewable energy also safeguards against another volatile commodity market: fossil fuels. While carbon-based energy prices are difficult to predict, the cost of renewable energy is certain across a project's lifetime. This reliability becomes especially valuable as an increasing number of jurisdictions adopt carbon taxes and cap-and-trade programs, adding a political dimension to an already unstable market.[65] The certainty of low-cost renewable electricity provides mine managers and investors the ability to improve forecasts and insulate assets against spikes in fossil energy prices.

4. Lastly, renewable energy installations are durable investments that bear value irrespective of mine operations. With the option to sell energy to local utilities, renewable infrastructure offers mines a guaranteed cash flow even during mine closure. This value proposition has led several large mining firms to partner with RMI to explore renewable energy systems on legacy mine sites that power nearby communities.[66]

Taken together, these factors do more than just provide value: they limit risk in an unpredictable global economy. As long-lived investments, resilient mines must be able to cope with fair and foul economic weather. Renewable energy offers a portfolio of economic, environmental, and social advantages to keep mines online and profitable far into the 21st century.

## FINANCING RENEWABLE INFRASTRUCTURE

The high capital costs of low-carbon energy pose the greatest barrier to renewables integration in metals production. Even when low-carbon energy undercuts the net present cost of fossil alternatives, the high price tag can cause sticker shock among risk-averse managers. Fortunately, a wide variety of financing instruments allows firms to benefit from renewable energy while outsourcing the capital required to a third-party investor.

The most common mechanism for installing renewable energy while avoiding the upfront costs comes in the form of PPAs. In a PPA, a large energy consumer contracts with a renewable energy developer and equity sponsor. This offsets the capital costs of renewable energy and provides a ready source of expertise to design and build a clean energy system. The parties to these agreements settle upon a fixed electricity price for the duration of the contract (usually 10–25 years), and the developer will rally the capital and expertise to build the infrastructure. This locks in a long-term energy price for the consumer while providing a guarantee for the developer that their low-carbon electricity will have a buyer.

These agreements work exceptionally well for some firms. Google has operated its offices and data centers with 100% renewable energy since 2017 (without the use of offsets). The tech giant entered into its first PPA in 2010 with a 114 MW wind farm in Iowa; today, it has 26 PPAs across four continents.[67] In sum, these agreements provide Google with nearly 3,000 MW of renewable capacity—equivalent to removing 1.3 million cars from the road each year.[68]

The same model has been used at mine sites and processing facilities around the world by firms that see value in de-risking their energy supply by locking in a price. In 2014, the Los Pelambres copper mine in Chile signed a PPA for a 104 MW solar plant.[69] And in 2016, the Peñoles zinc refinery in Northern Mexico signed a PPA for a 120 MW wind farm.[70] More recently, in June 2019, the Western Australian Agnew Gold Mine announced a PPA for a 4 MW solar array, an 18 MW wind farm, and a 13 MW/4 MWh battery storage system.[71] Part of the attraction of PPAs is their "turnkey" nature: they require no upskilling, no debt, and no added operational effort. In addition, PPAs can be located onsite or offsite, effectively resolving any issue of mines with land that is poorly suited to renewable energy (e.g., mountain terrain). In sum, PPAs allow mines to source renewable energy without getting into the renewable energy business.

An alternative to PPAs is direct ownership models. These usually involve debt or equity financing, and in some jurisdictions may allow for a tax equity investor. Direct ownership allows the mine to fully capture an energy asset's value by placing that infrastructure on a firm's balance sheet. Furthermore, directly owned assets have minimal OpEx. This model is best suited to mines with ready access to capital and an anticipated life of mine in excess of 10 years. By frontloading the cost burden (and the associated risk), mines are able to maximize return on their investment. Importantly, direct ownership also significantly improves a mine's cash position during a market downturn by reducing OpEx in the form of utility bills.

While the technoeconomic model presented here looks at direct ownership, the same principles apply to third-party or joint ownership, albeit with slightly lower returns. Thankfully, renewable energy developers have incentives that align with their energy buyers: to generate renewable electricity at below-grid prices.

## ACHIEVING NET-ZERO EMISSIONS

The pathway to 45% electricity decarbonization is technologically achievable and financially attractive. But 45% low-carbon electricity is a waypoint rather than a destination. For most copper mines (and other metals producers), the pathway above will only reduce emissions intensity by 20%–30%. If major emitters of greenhouse gases declare "mission accomplished" at this point, they leave the world on a dangerous trajectory to exceed 1.5°C warming. At this threshold, scientists predict that the consequences of climate change could become catastrophic for human societies and the environmental systems that sustain our food, water, and biosphere. For this reason, industry actors must view a 45% pathway as necessary but ultimately insufficient for creating a climate-stabilized future. The coming decades will require continued pressure to advance a new energy paradigm and ensure the sustainability of the metals sector.

The technologies that will enable 100% carbon-neutral mines are rapidly emerging. New innovations in renewable energy, electrification, productivity reforms, and metallurgical processes will pave the way toward total decarbonization of the mining sector. Many of these technologies are already in service in pioneering commercial operations or under development by researchers:

1. **Emerging renewable energy technologies** will offer opportunities for decarbonization of metals production. Hydrogen fuels offer an especially promising solution for storing energy and powering vehicles. For instance, the Glencore-owned Raglan nickel and copper mine, located at the extreme limit of Northern Québec, uses an Arctic-rated 3 MW wind turbine to power a hydrogen electrolyser.[72] The hydrogen, produced on-site with 100% clean electricity, powers the mine using fuel-cell technology that emits only water vapor and heat. The mining firm Anglo American has announced plans to produce a 300-ton hydrogen-powered haul truck by 2020.[73]

   Advances in battery technology will also reduce the costs of energy storage and allow greater integration of intermittent renewable energy. Bloomberg New Energy Finance predicts that the cost of lithium-ion batteries will halve by 2030, following an 85% per kilowatt-hour cost reduction from 2010–2018.[74] These advances will allow mines to harness carbon-free electricity even when the sun is low and winds are calm.

   In addition, modular and movable solar technologies are reducing the risk profile of low-carbon energy infrastructure. Cambridge Energy Partners, for instance, offers re-deployable solar systems. In 2018, Newmont Goldcorp installed a 120 kilowatt mobile solar array on a Ghanaian gold mine—the mine has a 10-year expected life, but the renewable energy system is rated for 25 years.[75] The solar array is producing electricity at 50% below grid prices and can be transported to another Newmont asset in the future, preserving the asset value and hedging against an early mine closure.

2. **Increasing electrification** of haul trucks, drill rigs, and processing machines will continue to reduce metals producers' dependence upon fossil fuels. As power grids around the world decarbonize their generation infrastructure, electrification alone can become an effective way to achieve deep decarbonization. Electric trucks and drill rigs are already being produced by Sandvik and Epiroc AB and deployed at full-scale, such as at the Borden Lake gold mine in Ontario.[76] The Finnish equipment manufacturer Metso also manufactures a mobile crushing plant with a fully electric drive. As vehicles and processing equipment become electrified, the opportunities to integrate renewable electricity increase as well.

3. **Energy productivity reforms** that allow mines to do more work with less energy are also mitigating the carbon footprint of metals. For instance, unmanned aerial vehicles are used by Freeport-McMoRan to collect regular topographic data on a mine in the

Democratic Republic of Congo, allowing for more efficient movement of material.[77] The hauling giant Caterpillar has developed fully autonomous vehicle fleets at mine sites in Western Australia. One such mine has reported a 20% productivity increase due to the automated hauling system.[78]

In-pit crushing and conveying is another example of efficiency reforms, in which mined ore is crushed underground or at the bottom of a surface mine and conveyed upwards only after the primary crushing process is complete. The conveyance systems then use high-efficiency electric belts to transport the ore for later-stage processing. The in-pit crusher at the Oyu Tolgoi copper and gold mine in Mongolia processes 95,000 tons of ore per day. The ore is then loaded onto a 10-kilometer-long electric conveyer system.[79] These processes eliminate the need for diesel haulers to shuttle back and forth between the mine pit and a crushing plant, where each trip with a full load of ore requires a return trip with an empty vehicle.

4. **New metallurgical processes** will also reduce the energy intensity of metal production.[80] These technologies vary widely in both inputs and readiness. But they all tend to share a common theme by requiring less energy to turn rock into usable metal. Biomining, for instance, uses naturally occurring bacteria to dissolve or oxidize valuable ore. It is used widely at commercial scale to produce copper, gold, and nickel from low-grade ore bodies, where sulfide ores make a welcome meal for certain bacteria.[81] And new innovations on producing steel with hydrogen could reshape the carbon footprint of this essential metal.

These innovations facilitate the production of zero-carbon minerals while safeguarding the health of miners and ensuring the stability of the earth's climate. As these technologies mature, they will become cost-effective stepping stones on the way to full decarbonization.

# CONCLUSION

A prosperous and climate-stabilized world needs critical minerals to facilitate a clean energy transition. But providing these resources requires low-carbon energy to be available at low cost. By relying on proven technology, firms stand to benefit from a "close follower" advantage that improves financial and environmental performance. With lower per-unit cash costs and increased resiliency, companies such as Rio Tinto and BHP are already harnessing the synergies between sustainability and fiduciary responsibility. In addition to this economic value proposition, these companies stand to gain political capital and reputational value with investors, consumers, political actors, employees, and local communities.

Firms that continue to leave options on the table risk letting opportunity costs balloon, placing mines in a precarious position amid soaring energy inputs and unpredictable commodities markets. "Business-as-usual" practices are already environmentally unsustainable, and their economic viability may prove to be similarly short-lived.

The critical demand for minerals such as copper highlights the dependency of global welfare upon the long-term success of mining companies. The pathway toward deep decarbonization must become an industry standard—a reliable supply of these metals and materials is necessary to secure a low-carbon and prosperous future.

# APPENDIX: METHODOLOGY

The 25 mine sites modeled renewable electricity supply for a generic mine—an “average” mid-size copper operation.[ii] The energy profile of each mine was based on an average load of 50 MW. The modeled load increased by 10% from 6:00 a.m. to 6:00 p.m. and decreased by 10% overnight. We also modeled hour-to-hour and day-to-day variability of 10%, which brought our analysis in line with the fluctuating energy demand of real-world mines.

Grid and fuel prices were regionally adjusted and accounted for time-of-use tariffs in Arizona. Power prices in Western Australia were sourced from Horizon Power. Prices for Peru were sourced from Enerdata. Prices for Mexico and Chile were sourced from the International Energy Agency of the Organisation for Economic Co-operation and Development.

Our technoeconomic analyses were designed to meet the following key performance indicators:

- IRR of at least 10%
- Payback period of fewer than 10 years
- Assumed discount rate of 7.5%
- Debt financing with 6% interest rates

Our models were built using HOMER Pro software, an industry-standard tool that was first developed at the United States’ National Renewable Energy Laboratory. The technical models produced by HOMER were further processed using the RMI industry financial models.

[ii] We assumed a sulfide ore operation with on-site processing into copper concentrate. For the purposes of our analysis, we did not find a need to distinguish between mine type or extraction process.

# ENDNOTES


1. Carbon Brief, "Explainer: These Six Metals Are Key to a Low-Carbon Future," April 12, 2018, **https://www.carbonbrief.org/explainer-these-six-metals-are-key-to-a-low-carbon-future**.

2. Florian Fizaine and Victor Court, "Renewable Electricity Producing Technologies and Metal Depletion: A Sensitivity Analysis Using the EROI," *Ecological Economics* 110 (February 2015): 106–18, **https://doi.org/10.1016/j.ecolecon.2014.12.001**.

3. Terry Norgate and Sharif Jahanshahi, *Energy and Greenhouse Gas Implications of Deteriorating Quality Ore Reserves* (Melbourne, Australia: 5th Australian Conference on Life Cycle Assessment, 2006).

4. Ayman Elshkaki et al., "Copper Demand, Supply, and Associated Energy Use to 2050," *Global Environmental Change* 39 (July 2016): 305–15, **https://doi.org/10.1016/j.gloenvcha.2016.06.006**; R. H. E. M. Koppelaar and H. Koppelaar, "The Ore Grade and Depth Influence on Copper Energy Inputs," *BioPhysical Economics and Resource Quality* 1, no. 2 (December 2016): 11, **https://doi.org/10.1007/s41247-016-0012-x**.

5. Susan Peters et al., "Estimation of Quantitative Levels of Diesel Exhaust Exposure and the Health Impact in the Contemporary Australian Mining Industry," *Occupational and Environmental Medicine* 74, no. 4 (April 2017): 282–89, **https://doi.org/10.1136/oemed-2016-103808**.

6. UNFCCC, "Paris Climate Agreement of 2015," accessed July 15, 2019, **https://unfccc.int/sites/default/files/english_paris_agreement.pdf**.

7. World Bank, "Climate-Smart Mining: Minerals for Climate Action," Text/HTML, accessed July 15, 2019, **https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action**.

8. B. Webster Smith, "60 Centuries of Copper", Copper Development Association, Inc., 1965, accessed November 17, 2019, **https://www.copper.org/education/history/60centuries/**.

9. Elshkaki et al., "Copper Demand, Supply, and Associated Energy Use to 2050."

10. "Climate-Smart Mining."

11. Elshkaki et al., "Copper Demand, Supply, and Associated Energy Use to 2050"; Ayman Elshkaki et al., "Resource Demand Scenarios for the Major Metals," *Environmental Science & Technology* 52, no. 5 (March 6, 2018): 2491–97, **https://doi.org/10.1021/acs.est.7b05154**.

12. Schipper et al., "Estimating Global Copper Demand until 2100 with Regression and Stock Dynamics." *Resources, Conservation and Recycling* 132 (May 1, 2018): 28–36. **https://doi.org/10.1016/j.resconrec.2018.01.004**.

13. World Meteorological Organization. "The Global Climate in 2015–2019." Geneva: WMO, 2019.

14. Fizaine and Court, "Renewable Electricity Producing Technologies and Metal Depletion."

15. International Energy Association, "IEA Statistics," 2019, **https://www.iea.org/statistics/kwes/consumption/**.

16. Koppelaar and Koppelaar, "The Ore Grade and Depth Influence on Copper Energy Inputs"; T. Norgate and S. Jahanshahi, "Low Grade Ores—Smelt, Leach, or Concentrate?," *Minerals Engineering* 23, no. 2 (January 2010): 65–73, **https://doi.org/10.1016/j.mineng.2009.10.002**; Elshkaki et al., "Copper Demand, Supply, and Associated Energy Use to 2050."

**17.** S. Northey et al., "Modelling Future Copper Ore Grade Decline Based on a Detailed Assessment of Copper Resources and Mining," *Resources, Conservation and Recycling* 83 (February 2014): 190–201, **https://doi.org/10.1016/j.resconrec.2013.10.005**.

**18.** Joeri Rogelj et al., "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development," in *Global Warming of 1.5°C*. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (IPCC, 2018), 82.

**19.** PricewaterhouseCoopers, "Mine Report 2019," accessed June 27, 2019, **https://www.pwc.com/gx/en/energy-utilities-mining/publications/pdf/mine-report-2019.pdf**.

**20.** PricewaterhouseCoopers.

**21.** PricewaterhouseCoopers.

**22.** "Climate-Smart Mining."

**23.** "Mining Companies Have Dug Themselves out of a Hole—The Richest Seam," *The Economist*, March 11, 2017, **https://www.economist.com/business/2017/03/11/mining-companies-have-dug-themselves-out-of-a-hole**; Henry Sanderson, "China's Demand for Electric Vehicles Charges Copper," *Financial Times*, February 11, 2019, **https://www.ft.com/content/8ae7dd6c-2df3-11e9-8744-e7016697f225**.

**24.** Frank Holmes, "Will 2019 Be the Year of King Copper?," *Forbes*, February 19, 2019, **https://www.forbes.com/sites/greatspeculations/2019/02/19/will-2019-be-the-year-of-king-copper/**.

**25.** "Goldman Sachs Flips from Copper Super-Bear to Super-Bull: Andy Home," *Reuters*, December 13, 2016, **https://www.reuters.com/article/us-copper-goldman-ahome-idUSKBN14222V**; Holmes, "Will 2019 Be the Year of King Copper?"

**26.** International Copper Study Group, "The World Copper Factbook 2018" (Lisbon, Portugal: International Copper Study Group, 2018), **http://www.icsg.org/index.php/component/jdownloads/finish/170/2876**.

**27.** Norgate and Jahanshahi, "Low Grade Ores—Smelt, Leach, or Concentrate?"

**28.** Northey et al., "Modelling Future Copper Ore Grade Decline Based on a Detailed Assessment of Copper Resources and Mining."

**29.** "Boliden Annual Report 2015," *Corporate Governance*, 2015, 124.

**30.** Elshkaki et al., "Copper Demand, Supply, and Associated Energy Use to 2050"; Koppelaar and Koppelaar, "The Ore Grade and Depth Influence on Copper Energy Inputs."

**31.** Norgate and Jahanshahi, "Low Grade Ores—Smelt, Leach, or Concentrate?"

**32.** Norgate and Jahanshahi; Elshkaki et al., "Copper Demand, Supply, and Associated Energy Use to 2050"; Nadine Rötzer and Mario Schmidt, "Decreasing Metal Ore Grades—Is the Fear of Resource Depletion Justified?," Resources 7, no. 4 (December 19, 2018): 88, **https://doi.org/10.3390/resources7040088**; Guiomar Calvo et al., "Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality?," Resources 5, no. 4 (December 2016): 36, **https://doi.org/10.3390/resources5040036**.

**33.** Simon Thompson, "Rio Tinto ESG Roundtable" (November 26, 2018), **https://www.riotinto.com/documents/181126_ESG_seminar_chairman.pdf**.

**34.** Terry Norgate and Sharif Jahanshahi, "Reducing the Greenhouse Gas Footprint of Primary Metal Production: Where Should the Focus Be?," *Minerals Engineering* 24, no. 14 (November 2011): 1563–70, **https://doi.org/10.1016/j.mineng.2011.08.007**.

**35.** Terry Norgate and William Rankin, *Life Cycle Assessment of Copper and Nickel Production* (Melbourne, Australia: MINPREX 2000: International Congress on Mineral Processing, 2000).

**36.** Northey et al., "Modelling Future Copper Ore Grade Decline Based on a Detailed Assessment of Copper Resources and Mining."

**37.** Koppelaar and Koppelaar, "The Ore Grade and Depth Influence on Copper Energy Inputs."

**38.** Peters et al., "Estimation of Quantitative Levels of Diesel Exhaust Exposure and the Health Impact in the Contemporary Australian Mining Industry."

**39.** Elshkaki et al., "Copper Demand, Supply, and Associated Energy Use to 2050."

**40.** Neil Hume, "Global Miners Tested by Shift to Low-Carbon Economy," *Financial Times*, December 27, 2018, **https://www.ft.com/content/3a2b90fc-0379-11e9-99df-6183d3002ee1**.

**41.** International Energy Agency (IEA), "World Energy Outlook 2018," 2018, **https://www.iea.org/weo2018/**.

**42.** Lazard, "Lazard's Levelized Cost of Energy Analysis—Version 12.0" (Lazard, November 2018), **https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/**.

**43.** Ben Caldecott et al., "Stranded Assets: A Climate Risk Challenge" (Inter-American Development Bank, November 2016), **https://doi.org/10.18235/0000517**.

**44.** Lazard, "Lazard's Levelized Cost of Energy Analysis—Version 12.0."

**45.** "Wind Technologies Market Report" (US Department of Energy, Office of Energy Efficiency & Renewable Energy, 2017), **https://www.energy.gov/sites/prod/files/2018/08/f54/2017_wind_technologies_market_report_8.15.18.v2.pdf**.

**46.** Thomas Koch Blank, "When Cheap Doesn't Cut It: Why Energy Buyers Should Look at Value, Not Just Cost," Rocky Mountain Institute (blog), May 1, 2018, **https://rmi.org/when-cheap-doesnt-cut-it-why-energy-buyers-should-look-at-value-not-just-cost/**.

**47.** Koch Blank, "When Cheap Doesn't Cut It."

**48.** Rio Tinto, "Energy and Climate Change," February 21, 2018, **http://www.riotinto.com/ourcommitment/energy-and-climate-change-24291.aspx**.

**49.** Thomas Kirk and Jessie Lund, "Decarbonization Pathways for Mines," Rocky Mountain Institute, August 20, 2018, **https://rmi.org/mining-for-emissions-reductions-strike-while-the-earth-is-cool/**.

**50.** Independent Electricity System Operator of Ontario, "2018 Electricity Data," 2019, **http://www.ieso.ca/en/Corporate-IESO/Media/Year-End-Data**.

**51.** Koch Blank, "When Cheap Doesn't Cut It."

**52.** Australia Renewable Energy Agency (ARENA), "Media Release: Gold Fields Gold Mine to Be Powered with Wind, Solar and Battery," June 19, 2019, **https://arena.gov.au/assets/2019/06/ARENA-Media-Release_-Gold-Fields-Renewable-Hybrid-Powers-Mine-190619.pdf**.

**53.** Barrick, "Zaldívar Goes For 100% Renewable Electricity," accessed July 24, 2019, **https://www.barrick.com/news/news-details/2018/zaldivar-goes-for-100-percent-renewable-electricity/default.aspx**.

**54.** Rocky Mountain Institute, "Renewable Resources at Mines Tracker," 2019, **https://rmi.org/our-work/electricity/sunshine-for-mines/renewable-resources-at-mines-tracker/**.

**55.** Annie Benn et al., "Managing the Coal Capital Transitionn: Collaborative Opportunities for Asset Owners, Policymakers, and Environmental Advocates" (Rocky Mountain Institute, 2018), **https://rmi.org/insight/managing-coal-capital-transition/**; Nick Fitzpatrick et al., "Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution" (Report for the UK Department of Transport, 2018), **https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815671/identification-market-failures-other-barriers-of-commercial-deployment-of-emission-reduction-options.pdf**.

**56.** Billy Nauman, "Global Banks Agree Framework to Promote Green Shipping," *Financial Times*, June 18, 2019, **https://www.ft.com/content/51cf5cee-912b-11e9-b7ea-60e35ef678d2**.

**57.** "Rio Tinto Talking to Apple on next Step of Carbon-Free Aluminum Project," Reuters, March 9, 2019, **https://www.reuters.com/article/us-australia-rio-tinto-bauxite-idUSKCN1QP1ED**.

**58.** John Weaver, "Los Angeles Seeks Record Setting Solar Power Price under 2¢/KWh," *PV magazine*, June 28, 2019, **https://pv-magazine-usa.com/2019/06/28/los-angeles-seeks-record-setting-solar-power-price-under-2%C2%A2-kwh/**.

**59.** Gideon Long, "Chile Launches Its Biggest Wind Farm," BBC News, August 27, 2014, sec. Latin America & Caribbean, **https://www.bbc.com/news/world-latin-america-28950685**.

**60.** Australia Renewable Energy Agency (ARENA), "Media Release: Gold Fields Gold Mine to Be Powered with Wind, Solar and Battery."

**61.** "AGL Secures Right to Develop Pumped Hydro Energy Storage Project in South Australia I AGL," accessed July 25, 2019, **https://www.agl.com.au/about-agl/media-centre/asx-and-media-releases/2019/april/agl-secures-right-to-develop-pumped-hydro-energy-storage-project-in-south-australia**.

**62.** "The Renewable Power of the Mine: Accelerating Renewable Energy Integration" (Columbia Center on Sustainable Investment, December 2018), **http://ccsi.columbia.edu/files/2018/12/3418-CCSI-RE-and-mining-report-09-lr-reduced-optmized-07-no-links.pdf**.

**63.** Tyler Stehly et al., "2017 Cost of Wind Energy Review" (National Renewable Energy Laboratory, 2018).

**64.** Ran Fu, Timothy Remo, and Robert Margolis, "2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark," *Renewable Energy*, 2018, 32.

**65.** World Bank, "State and Trends of Carbon Pricing 2019" (Washington, D.C.: World Bank Group, June 2019).

66. Rocky Mountain Institute, "A Second Life For Legacy Mining Sites," accessed July 26, 2019, **https://d231jw5ce53gcq.cloudfront.net/wp-content/uploads/2017/11/RMI_SecondLifeLegacyMiningSites.pdf**.

67. Google, "2018 Environmental Report," accessed August 12, 2019, **https://storage.googleapis.com/gweb-sustainability.appspot.com/pdf/Google_2018-Environmental-Report.pdf**; "Google Signs First Solar PPA in Asia," *pv magazine*, January 23, 2019, **https://www.pv-magazine.com/2019/01/23/google-signs-first-solar-ppa-in-asia/**.

68. Google, "2018 Environmental Report."

69. Photon, "Chilean Mining Company Los Pelambres Signs PPA to Buy Electricity from 104 MW PV Plant," February 10, 2014, **https://www.photon.info/en/news/chilean-mining-company-los-pelambres-signs-ppa-buy-electricity-104-mw-pv-plant**.

70. Andrew Slavin, "200MW Wind Farm for Mexican Mine Nears Completion," *Energy and Mines* (blog), September 23, 2016, **https://energyandmines.com/2016/09/project-update-penoles-coahuila-wind-farm-to-be-completed-in-2016/**.

71. Australia Renewable Energy Agency (ARENA), "Media Release: Gold Fields Gold Mine to Be Powered with Wind, Solar and Battery."

72. "Raglan I—Hybrid Wind, Diesel, and Storage Energy Generation in Arctic Canada," Tugliq Energie (blog), accessed July 25, 2019, **http://tugliq.com/en/realisation/raglan-i/**.

73. FuelCellsWorks, "Anglo American Sets One Year Goal for Hydrogen Trucks," *FuelCellsWorks* (blog), accessed August 2, 2019, **https://fuelcellsworks.com/news/anglo-american-sets-out-one-year-goal-for-hydrogen-trucks/**.

74. Veronika Henze, "Energy Storage Investments Boom As Battery Costs Halve in the Next Decade," *Bloomberg New Energy Finance*, July 31, 2019, **https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/**.

75. "Newmont Akyem Case Study," *Cambridge Energy Partners* (blog), May 30, 2019, **https://cambridge-ep.com/newmont-akyem-case-study/**.

76. "Sandvik Mining and Rock Technology—Mining Equipment, Parts, & Services," accessed July 26, 2019, **https://www.rocktechnology.sandvik/en/**; Raghav Muralidharan, Thomas Kirk, and Thomas Koch Blank, *Exploring Pathways to Decarbonize Bulk Material Hauling in Mining* (Boulder, CO: Rocky Mountain Institute, 2019), **https://rmi.org/insight/pulling-the-weight-of-heavy-truck-decarbonization/**.

77. Kirk and Lund, "Decarbonization Pathways for Mines."

78. Caterpillar, "Realizing the Benefits of Autonomy," Caterpillar/Viewpoint Mining, 2019, **https://www.cat.com/en_US/articles/customer-stories/mining/viewpoint/autonomous-haulage-gains.html**.

79. Ergo Strategy Group, "Oyu Tolgoi—Past, Present, and Future," August 2018, **https://www.riotinto.com/documents/RT_Oyu_Tolgoi_Past_Present_and_Future_EN.pdf**.

80. Thomas Koch Blank, *The Disruptive Potential of Green Steel* (Boulder, CO: Rocky Mountain Institute, 2019), **https://rmi.org/insight/the-disruptive-potential-of-green-steel/**.

81. American Geosciences Institute, "What Is Biomining?," September 19, 2017, **https://www.americangeosciences.org/critical-issues/faq/what-biomining**.

ROCKY MOUNTAIN INSTITUTE

22830 Two Rivers Road
Basalt, CO 81621 USA
www.rmi.org