Applied Energy 300 (2021) 117375

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches

Tsisilile Igogo [a], Kwame Awuah-Offei [b], Alexandra Newman [c,*], Travis Lowder [a], Jill Engel-Cox [a]

[a] National Renewable Energy Laboratory, Joint Institute for Strategic Energy Analysis, Golden, CO 80401, United States of America
[b] Mining & Nuclear Engineering Department, Missouri University of Science and Technology, Rolla, MO 65409, United States of America
[c] Mechanical Engineering Department, Colorado School of Mines, Golden, CO 80401, United States of America

ARTICLE INFO

Keywords:
Mining
Energy integration
Renewable energy
Clean-energy technologies
Battery storage

ABSTRACT

Mining is one of the most energy-intensive industries worldwide. It also provides a critical source of raw materials for the manufacturing, transportation, construction, and energy sectors. Demand for raw materials is projected to increase as the world population grows and many low-income economies become middle-income countries. This growth in mineral demand, coupled with falling mineral ore grade, will likely increase the mining industry's energy demand, used for activities across exploration, extraction, beneficiation and processing, and refining. At the time of this writing, mine operations are – due to their remoteness – dependent on fossil fuels such as diesel, heavy oils, and coal. In principle, mining could use energy recovery, renewable energy, and carbon capture to supplement, replace, or mitigate the impacts of fossil fuel use. However, a combination of renewable-energy technologies would be required. We explore challenges, opportunities, and enabling approaches to integrate renewable energy technologies into mining operations by examining the literature, including academic work, technical reports, and data produced by international agencies. We find that despite numerous opportunities, technical issues still need to be considered, but solutions can tailor renewables to the mining industry. Further research should focus on identifying specific opportunities, technologies, and implementation strategies across the value chain of a variety of minerals with similar operational procedures.

1. Introduction

The mining industry, defined by the activities covered under exploration, extraction, beneficiation, processing, and refining, provides a critical source of raw materials for many industries such as manufacturing, transportation, construction, energy, and the mining industry itself. It is anticipated that demand for raw materials will increase as the population grows and many low-income economies shift to middle-income status [1]. The increase in mineral demand, combined with declining mineral ore grades, is expected to increase energy demands of the mining industry, which will potentially expand its already large greenhouse gas footprint [2,3]. Materials derived from mining processes are heavily embodied in the global economy and will continue to play a critical role in the future of humanity [4]. Correspondingly, the environmental impacts of these mining activities will need to be addressed. In principle, mining could use energy recovery, renewable energy, and carbon capture to lower its energy consumption and decrease greenhouse gas emissions. A combination of renewable-energy technologies will be required to fully address energy-related challenges facing the mining industry.

1.1. Research issues and motivation

This paper explores the challenges, opportunities, and enabling approaches to integrate renewable technologies into mining operations. Partly to combat its potentially expanding greenhouse gas profile, the mining industry is increasingly adopting renewable energy to power its operations. This uptick in adoption has been driven by several factors, including energy costs, corporate environmental goals, and social license-to-operate considerations. In 2015, there were 600 MW of renewable energy projects sited on or serving mine sites. By the end of 2019, there were nearly 5 GW of renewable energy projects installed at or planned for mine sites around the world [5]. This growth, however, has not been without headwinds. Around-the-clock mining operational loads, the distinctive nature of energy demand, inflexible contracting

* Corresponding author.
E-mail addresses: Tsisilile.Igogo@nrel.gov (T. Igogo), kwamea@mst.edu (K. Awuah-Offei), anewman@mines.edu (A. Newman), Travis.Lowder@nrel.gov (T. Lowder), jill.engelcox@nrel.gov (J. Engel-Cox).

https://doi.org/10.1016/j.apenergy.2021.117375
Received 22 February 2021; Received in revised form 17 May 2021; Accepted 4 July 2021

structures, space constraints at the mine site, and policy and regulatory barriers have inhibited adoption of renewable energy technologies at scale.

Mining can be divided into two main energy-use categories: off-grid and grid-connected. Traditionally, most off-grid mining operations depend on fossil fuels such as diesel, heavy oils, and coal for on-site generation and haulage [6]. However, grid-connected mining operations are also reliant on fossil fuels, to some degree. The grid, where available, often provides the least costly source of energy, and, as such, is typically preferred by the mining industry over self-generation. In many countries with unreliable grid supply, most grid-connected operations have additional on-site generation as backup. These are mostly sourced from fossil fuels, which adds to the cost of production.

Energy is one of the most significant expenses for the mining industry, comprising some 15%–40% of total operating costs, on average [7]. With such a large proportion of expenditures devoted to energy production, and such a significant portion of that energy sourced from fossil fuels, the mining industry is highly exposed to fossil-fuel-market volatility. Energy demand in mining operations is anticipated to grow as much as 36% by 2035 [7].

Aside from the economics, the dependence on fossil fuels for mining also impacts the well-being of local communities and has implications for local infrastructure, air and water quality, and the environment. Moreover, pressure is increasing from further down the value chain, where raw material purchasers are beginning to require that their suppliers demonstrate sustainability in operations. All of these factors – economic, societal, and environmental – are motivating a reconsideration of how energy is generated and used at mining sites. We hypothesize that renewable energy integration into mining operations can address these pressures. Decreasing costs in wind, solar, geothermal, storage, and other renewable technologies are driving adoption worldwide [8]. A growing renewables market, in turn, means higher demand for minerals and metals (including iron, nickel, lithium, platinum, and cobalt), which benefits mining companies and can create circular economies between the two industries.

1.2. Literature review

Mining is energy intensive, consuming about 38% of global industrial energy use, 15% of the global electricity use, and 11% of global energy use. The total global energy use by the mining industry comprises about 19% of global coal and coal products, 5% of global gas, and 2% of global oil supplied [9,10]. The US Department of Energy (DOE) has estimated that the nation's mining sector consumes about 1315 PJ of energy per annum, whereas mining in South Africa consumes 175 PJ per annum [11,12]. In many developing economies, energy demand from the mining sector is a significant (over 50% in Zambia and Democratic Republic of Congo) portion of overall energy consumption [12,13]. Because of their energy intensity, mining operations tend to emit high levels of greenhouse gases, leading to significant climate change impacts [14,15], which many stakeholders recognize need to be reduced [16,17]. This is especially important because mining will play a significant role in providing materials necessary for the transition towards a low-carbon energy infrastructure [18,19].

Climate change impacts of mining, as measured, for example, using life cycle global warming potential, are closely associated with energy consumption. For example, Norgate and Haque [15] show that global production of copper concentrate is responsible for 30 Mtpa of CO_2-eq, while the production of iron ore and bauxite are responsible for 17 Mtpa and 0.8 Mtpa of CO_2-eq, respectively. While reducing the energy intensity of mining can reduce its climate change impact to an extent [14,15], the mining sector needs to decrease its reliance on fossil fuels to reduce its carbon emissions.

Stakeholders have been working on means to increase renewable energy in the generation mix used by the mining industry to reduce greenhouse gas emissions. Previous research has highlighted various opportunities for including renewable energy in mining projects [20,21]. Attempts to integrate renewable energy should be aligned with the identified energy-intensive unit processes, which include material handling, comminution, thermal process and metal refining [9,10] in order for renewable integration to produce the desired outcomes.

There is an emerging body of literature on how the mining industry might integrate more renewable energy into its operations, classified as follows: (i) literature that focuses on particular mining contexts (typically, remote or off-grid mines), (ii) work that relates to specific renewable technologies, and (iii) research that focuses on a particular region. The first group includes work that evaluates the potential for renewable integration for mines that: are located in remote locations; are often off-grid; and possess significant costs for transporting diesel fuel, if they rely on diesel generators [22,23]. This group also includes work that provides analysis for particular commodities or types of mines. Examples include Stegen [24] and Dutta et al. [25], who examine renewable energy in rare earth minerals extraction. The second group includes work that evaluates specific renewable technologies, e.g., wind and photovoltaic systems [23]. The last group evaluates opportunities and challenges for renewable integration in particular countries [26,27]. For example, Furnaro [27] reviews renewable opportunities for mining in Chile while Baker [26] and Votteler and Brent [28] do the same for South Africa.

There is, however, limited work that examines the entire industry comprehensively to identify broad opportunities and challenges to facilitate pre-competitive research that can motivate the industry to integrate renewables, although there are a few compelling examples [29,30]. In 2020, there were about 5GW of cumulative renewable energy projects commissioned or planned for mining operations [31]. But, this renewable capacity is still a fraction of total energy demanded by mining operations; thus, the question remains as to why renewable energy use in the mining industry is developing at such a slow pace. This paper builds on work done by Maennling and Toledano [7] to answer this question by identifying opportunities, barriers of integrating renewables, and enabling approaches to accelerate the use of renewables in mining operations. The main contribution of this paper, therefore, is to identify challenges that slow renewable integration in the mining industry (such as technology readiness) to fit energy demand and research and development gaps. We next provide an overview of the mining industry — including energy use in the industry and the resulting emissions, and the potential for adoption of renewables.

The remainder of this paper is organized as follows: Section 2 provides an overview of the mining industry. Section 3 discusses renewable integration opportunities; in the latter part of this section, we describe case studies. Section 4 highlights technical considerations for renewable integration in mining operations, and then poses challenges for renewable integration in mining operations. Section 5 offers enabling approaches; and, Section 6 concludes.

2. Overview of the mining industry and its operations

We next provide background for and an overview of the mining industry and its associated operations, and then present the energy challenges associated therewith.

2.1. Mining industrial structure, energy use and carbon emissions

The global metals and mining sector produced 9830.8 million tonnes of product in 2018 for total revenues of $2643.3 billion [35]. Mining and quarrying materials can be divided into four main groups: industrial minerals, metal minerals, aggregates, and mineral fuels. This paper focuses on the first three categories, excluding mineral fuels as they have been addressed elsewhere in the literature [36]. Generally, commodity prices are cyclical, leading to booms and busts that tend to inhibit significant investments with long payback periods. Even in

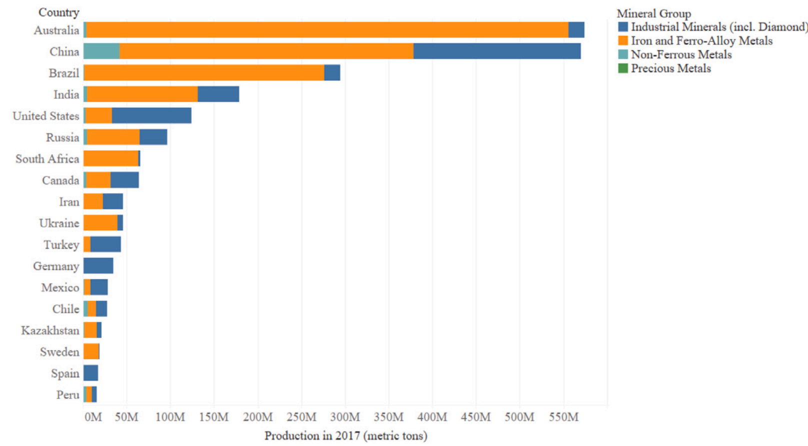

Fig. 1. Leading minerals producers.
Source: [32].

Table 1
Energy use and greenhouse gas impacts for 'Cradle-to-Gate' of select metals.
Sources: [33] and [34].

Metal	Feed	Process or route	Greenhouse gasses (kWh/t)	Gross energy requirement ($MtCO_2$-eq/Mt)
Gold	Refractory ore (3.5 g Au/t ore)	Refractory ore route	85,019,200	26,840
	Non-refractory ore (3.5 g Au/t ore)	Non-refractory ore route	55,829,200	17,560
Titanium	Ilmenite (36.0% Ti)	Becher and Kroll processes	101,080	35.7
Aluminum	Bauxite ore (17.4% Al)	Bayer refining, Halle Heroult smelting	59,080	22.4
Nickel	Laterite ore (1.0% Ni)	Pressure acid leaching, and solvent extraction and electrowinning	54,320	16.1
	Sulfide ore (2.3% Ni)	Flash furnace smelting and Sherritt-Gordon refining	31,920	11.4
Stainless Steel	Multiple ores	Electric furnace and Argone Oxygen decarburization	21,000	6.8
Copper	Sulfide ore (2.0% Cu)	Heap leaching, and solvent extraction and electrowinning	17,920	6.2
Zinc	Sulfide ore (5.5% Pb, 8.6% Zn)	Electrolytic process	13,440	4.6
	Sulfide ore (5.5% Pb, 8.6% Zn)	Imperial smelting process	10,080	3.3
Copper	Sulfide ore (3.0% Cu)	Smelting and converting and electro-refining	9240	3.3
Lead	Sulfide ore (5.5% Pb, 8.6% Zn)	Imperial smelting process	8960	3.2
Lead	Sulfide ore (5.5% Pb, 8.6% Zn)	Lead blast furnace	5600	2.1
Steel	Iron ore (64% Fe)	Integrated route (blast (oxygen) furnace)	6440	2.3

Notes: Multiple ores under stainless steel represent pig iron (94% Fe), chromite ore (27.0% Cr, 17.4% Fe), and laterite ore (2.4% Ni, 13.4% Fe). The gross energy requirement represents the cumulative amount of primary energy consumed from extracting to refining metal.

periods of high commodity prices, the cost of producing from lower grade ores to meet increased demand tends to increase unit operating costs, thus limiting shareholder returns. The sector is also heavily regulated because of societal interests in managing mineral endowments (e.g., policies on royalties and government tendency to increase returns to governments in periods of high commodity prices), health and safety of miners, and environmental impacts of mining. In many countries, the size of the mining sector makes its influence on energy and other policy significant. For example, developing countries with over 50% of their energy generation dedicated to mining [13] cannot afford to allow the sector to install significant renewable generation with guarantees to buy back excess power. Consequently, even though the sector has increased renewable capacity, several unique factors have limited the rate of renewable integration. These are discussed in Sections 2.2 and 4.

Fig. 1 ranks the largest producers of minerals in the world and categorizes their production into subgroups. Note the particularly high volume of iron and ferro-alloy metals – which include steel and stainless steel – produced worldwide. All energy requirements associated with the extraction of iron ore as well as the production of steel products represent a sizable opportunity for renewables to play a role in decarbonization.

Generally, mining consists of ground fragmentation (including drilling and blasting), excavation, loading, transportation, beneficiation and processing, and smelting and refining. These operations make the mining industry one of the most energy-intensive businesses. Total energy demand for mining is anticipated to grow over the near- to mid-term. Without significant adoption of renewable energy technologies in the mining industry, most of this new demand will be met with fossil fuels.

Table 1 shows the "cradle to gate" energy use and greenhouse gas impacts of select metals worldwide, where we define "cradle to gate" as raw material extraction to refining [33]. Based on these data, gold extraction is one of the most energy- and emissions-intensive mining activities — excluding platinum mining. This is in large part due to increasing ore depletion, which forces miners to extract gold ore from reserves lying deeper underground. About 3340 Metric tons (Mt) of gold was produced in 2017, according to the World Mining Database. Assuming the energy intensity and greenhouse gas emissions per ton of gold extracted are still the same as 2007 estimates (see Table 1), then roughly 186 to 283 terawatt hours (TWh) of energy was used to produce gold in 2017, yielding about 58 to 90 million Mt of CO_2 emissions globally as a result of that mining.

While steel requires less energy and produces less CO_2 than gold per ton of metal production (Table 1), the high volume of global iron and steel production, as well as the process emissions and high heat requirements in steelmaking, render iron and steel production the highest consumer of energy and producer of greenhouse gas emissions within

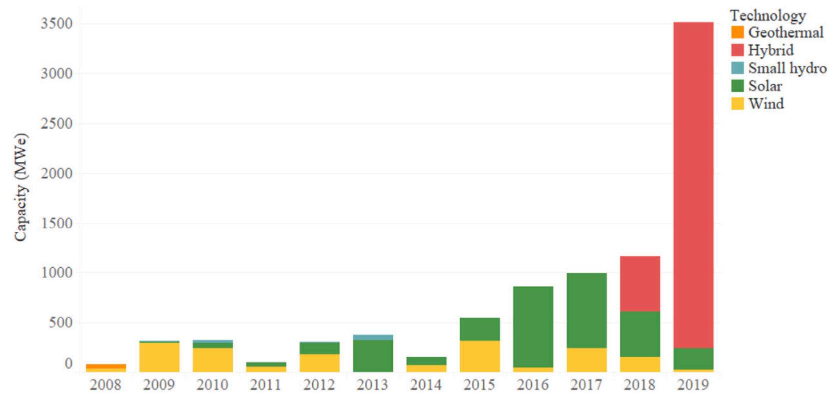

Fig. 2. Global renewable projects associated with mining companies. *Source:* [31].

the mining industry. For example, in 2018, crude steel production was about 1808 million tons [37]. Assuming that the energy and emission intensity of steel in 2018 is similar to the intensity in 2007 (Table 1), that would mean the steel industry used about 11,644 TWh of energy and produced about 3616 million Mt of CO_2 emissions.

Fig. 2 shows renewable project trends from 2000 to 2019. (Prior to 2000, the use of renewables in mining operations was nearly non-existent.) Recent years have seen an uptick in renewable energy adoption by mining companies, with a notable spike in commissioned projects in 2019. This renewable installation has increased from 42 MW annually in 2008 to 3397 MW in 2019 [31]. Most of the systems in 2018 and 2019 are hybrids – i.e., a combination of wind, solar, energy storage, and other technologies – generally backed by fossil fuels to smooth the variability of the renewable energy generation (see Fig. 2).

2.2. Challenges and factors of interest in renewable energy use in mining operations

This section discusses the principal issues shaping the mining industry at the time of this writing and how these are driving interest in renewable energy use in mining operations.

Declining Ore Grades

Depletion of higher grade and easily accessible ores has driven mining companies to seek resources that are more remote and deeper in the ground. Falling ore grades also means that more materials need to be extracted, loaded, hauled, transported, and processed than would otherwise be necessary to produce the same amount of metal or minerals. This intensifies the energy requirements for mine operations. For example, a decrease in copper ore grade between 0.2% to 0.4% requires seven times more energy than present-day operations [3].

Studies suggest that declining ore grades, combined with increasing demand for metals, will exacerbate the greenhouse gas emissions impact from primary metal production [2]. This presents the mining industry with the dual challenges of seeking decarbonization measures while at the same time facing the prospect of growing energy demand. Additionally, the increasing remoteness of mines presents energy supply chain issues, which can have greenhouse gas and cost implications in the form of available fuel types, transportation needs, site access and infrastructure measures.

Volatile Prices

The mining industry is susceptible to supply and demand shocks that affect energy and metal prices because these, in turn, affect the cost of production and revenue. Ultimately, increasing costs and decreasing revenues can translate to thinner profit margins. Energy is one of the largest expenses in mining. On average, this expense ranges from 15% to 40% of the total operational cost [7]. In the mining and quarrying sectors, 57% of energy consumed comes from fossil fuels; specifically, of this 57%, 33% is derived from oil products, 13% stems from coal, and 11% emanates from natural gas. Electricity (from various sources) accounts for 40% of energy consumption by the mining and quarrying sectors and heat some 3% — mostly generated from combustible fuels [38]. Fossil fuels supplied to many mining operations must be imported, which exposes them to exchange rate differences and tariffs, supply chain logistics, and geopolitical risk. For example, between 2011 and 2014, oil was mostly trading above $100 per barrel but, at the time of this writing, has dropped to an average of $45 per barrel. Energy price fluctuations, in combination with declining metal prices, present major concerns for mining industry profitability.

Increasing Environmental Concerns

There are two primary ways in which mining operations can significantly impact the environment, both at the local and global levels: (i) equipment and other mechanized systems associated with the execution of mining activities can emit greenhouse gasses and other toxins; and, (ii) mining activities such as blasting and processing can generate waste containing toxic chemicals. These mining activities can lead to soil erosion, land use impacts, air pollution, and contamination of water sources and soil [39]. As the industry searches for more difficult-to-extract mineral resources in ecologically sensitive areas, environmental concerns are expected to increase the level of scrutiny. This is one of the reasons that the International Council on Mining and Metals requires its members to address environmental concerns [40].

Increasing Political and Social Concerns

At the same time, the mining industry is experiencing increasing pressure from its shareholders and external stakeholders to reduce dependence on fossil fuels and to address inter-generational equity issues. These stakeholders include international organizations, host governments, local communities, and end-use producers (metal buyers) such as major electronics and renewable energy technology manufacturers [16,17]. Recognizing the important role that the mining industry can play in achieving emissions targets, host countries are beginning to require more stringent pollution controls and statutory reporting requirements (e.g., the inclusion of the effects of energy consumption in environmental impact assessments to obtain an operating permit). For example, host governments of leading mineral producers such as Canada, Australia, and Chile are creating enabling policies and regulations such as carbon taxes, green certifications, and flexible dispatch to accommodate renewable sources integration [41,42]. The communities in which mines operate are beginning to mobilize as well, advocating not only for their local air and water quality, but also for a fair portion of the resources, and for lasting, sustainable energy infrastructure from which they could benefit after the mine closes. Accordingly, as energy demand for mine operations increases in the coming years, so too will the need to source generation that addresses stakeholder concerns.

Table 2
Example of mining processes and associated fuel sources.

Mining process	Activities and equipment	Fuel source
Exploration, extraction and auxiliary operations	Ventilation: HVAC	Electricity and Natural Gas
	Drilling: Loader trucks, diamond drills, rotary drills, percussion drills, drill boom jumbos	Electricity, Diesel, and Compressed Air
	Dewatering: Pumps	Electricity
	Digging: Hydraulic shovels, cable shovels, continuous miners, longwall mining machines, drag lines, front-end loaders	Electricity and Diesel
	Power supply: Generators	Fossil Fuel
Material handling	Discrete transportation systems: Haul trucks, service trucks, bulldozers, pickup trucks, bulk trucks, load-haul dumps, shuttle cars, hoists	Diesel and Electricity
	Continuous transportation systems: Conveyor belts, pumps, pipelines	Electricity
Beneficiation and processing	Communition	Electricity
	Crushing: Crushers	
	Grinding: Mills	
	Separations:	Electricity and Fossil Fuels
	Physical: Floating, centrifuge	
	Chemical: Electrowinning	
	Drying, Firing, Smelting (oven and furnace)	Fossil Fuels
	refining e.g., electrolytic refining, fire refining	Electricity and Fossil Fuels

3. Opportunities for integrating renewable energy in mining operations

Renewable energy technologies such as wind and solar have recently become the cheapest source of power on a levelized-cost-of-energy basis in many parts of the world, and capital costs for these also continue to fall [43]. Accordingly, integrating renewable generation into mining operations may offer an opportunity for companies not only to decarbonize operations, but also to improve operating margins and reduce risks associated with fossil fuel volatility. Mining companies and national governments can also realize secondary effects with renewable energy, such as stimulating local economic development, improving social license to operate, and creating shared value. We divide renewable integration opportunities in the mining industry into two main categories, those for mining operations and those for mining communities.

3.1. Opportunities for mining operations

Several mining activities rely on electric power, but most electricity generation is fossil fuel-fired, and, thus, may be satisfied by renewable energy. While on-grid mining operations may have no choice as to their source of electricity (in this case, greening grid systems could be a viable option), off-grid mining operations and back-up electricity for on-grid power could benefit from renewable integration into their operations. Also, there are mining operations in both grid-connected and off-grid sites that use fossil fuels directly as a source of energy or feedstock that can benefit from renewable sources (see, for example, Table 2).

In the United States, the majority of primary metal and non-metallic mineral production uses fossil fuels for various operations beyond extraction. Metal production generally consumes more energy than nonmetallic minerals. The bulk of this energy consumption (about 70%) is from the iron and steel industry, followed by the alumina and aluminum industries at 14% [44]. For nonmetallic mineral production, the majority of energy consumption is used by the cement industry at 30%, followed by glass industry at 14% and the lime industry at 12%.

Most energy is used for process heat, with a significant amount sourced from fossil fuels (mostly natural gas and coal in the United States). This implies that a significant reduction of fossil fuel used in mining operations can be achieved by targeting process heat, though, as discussed in Section 4, this presents some challenges. After natural gas, electricity is the second major source of energy in U.S. primary metal production, and is used mainly for process heat, machine drive and electrochemical processes. Likewise, in nonmetallic mineral production, most electricity is used for machine drive and process heat. In contrast to process heat, this electricity load can be readily supplied with renewable energy, particularly hybrid systems or virtual crediting contracts that can smooth the variability of the generation profile.

Renewables for electricity demand

Renewables can play a role in displacing heavy oil fuels, diesel, and coal used for electricity-dependent mining operations (see Table 2). For example, comminution (the process of reducing ore and/or rock to desired sizes by mechanical means) is one of the most electricity-intensive activities in mining [11]. Katta et al. [45] estimated that comminution uses an average of 15% of total energy demand in iron mining and an average of 21% of total energy demand in gold production. Fortunately, comminution is almost exclusively electrified, making it easier to address with renewable sources. This study also indicated that underground mining ventilation systems use significant electricity — in gold production, about 20% of total energy demand is used in ventilation. In the United States, electricity is used for processing metals, especially to generate process heat, for machine drive and in electrochemical processes. But, 63% of this electricity comes from fossil fuels. For off-grid mining operations, electrifying this electricity load is possible, but for on-grid operations, this opportunity may not present itself. Rather, greening the grid may be a viable option; this is out of our scope, but has been covered extensively by other studies [46].

Electricity generation for off-grid operations or on-site backup for on-grid operations can be powered with renewable sources. (For on-grid operations, in certain markets, excess renewable electricity can be sold back to the grid.) Renewables are becoming an increasingly appealing option for remote, off-grid operations that have available resources (e.g., sun, wind, geothermal). Rio Tinto is planning to build a 34 MW solar PV with a 12 MWh lithium-ion battery system to meet its electricity demand in their Koodaideri mine in Pilbara, Australia [47]. This system will meet about 65% of the Koodaideri mine's electricity demand during peak hours. Success stories of mines using geothermal power in remote sites of Papua New Guinea, and wind power in the Arctic of northern Canada illustrate the effectiveness of renewables in serving remote facilities [48,49]. Solar power in the Outback of Australia provides yet another example [50]. Fig. 3 depicts a solar installation at Rio Tinto's Weipa bauxite mine in Australia.

Renewables to replace fossil fueled heat and transportation

There are mining industry activities that depend on direct combustion of fossil fuels. In this case, fossil fuel is used to generate heat for mining processes such as firing in iron mining or as fuel to power

Fig. 3. Solar installation at Rio Tinto's Weipa bauxite mine in Australia. Copyright: Australian Renewable Energy Agency.

equipment used for ventilation, hauling and on-site transportation. Some of these activities may be transitioned to electric loads with the electricity provided by renewable technologies, while others may use renewable energy directly.

Table 2 categorizes these loads under auxiliary operations, material handling, beneficiation, and processing. While material handling may not be electricity-intensive in mineral manufacturing (EIA, 2014), in ore production, energy consumption by material handling is significant and will need to be addressed if the mining industry is to reduce its carbon footprint. Transport and haulage, for example, use about 10% of total energy demand in gold production and iron ore extraction [45]. Integrating renewables into material handling is more challenging because diesel is still a significant source of energy for many of these activities, particularly for truck haulage. However, the industry has started to use battery-powered and biodiesel trucks and load-haul-dumps, and is also exploring hydrogen-powered haulage. At the time of this writing, underground mines provide cutting-edge examples because of the need to comply with diesel particulate matter emissions standards. This motivation does not exist for surface mines (that also have larger equipment). Additionally, electrifying mobility for underground mines can result in economic offsets in the avoided cost of ventilation equipment [51]. Surface mines can benefit from technologies such as electric trolley-assist, combined with other solutions (e.g., biodiesel and energy recovery during braking on the downhill haul), to reduce fossil fuel use [52,53].

Renewables for feedstock demand

Some mining activities require fossil fuels as feedstock in their production processes. Coal and natural gas comprise the majority of feedstocks in the mining industry, and – while it is challenging for renewables to entirely displace these – some studies suggest that renewable sources can supply 20%–30% of fossil fuel feedstock demand for industrial minerals, and ferrous-alloy and non-ferrous metal producers [54]. For example, steel production using smelting reduction largely relies on coal as feedstocks to produce coke needed in blast furnaces and blast oxygen furnaces, from which around 70% of global steel is produced. On average, 1000 kg of crude steel produced by this route uses 780 kg of metallurgical coal [55]. Additionally, both coal and natural gas are used as reducing agents in the direct-reduced iron production process. In a gas-based, direct-reduced iron plant, natural gas is combined with water and heat to develop hydrogen and carbon monoxide needed to convert iron ore to direct-reduced iron, while in a coal-based, direct-reduced iron plant, carbon from coal is used as a reducing agent [56]. Biomass and hydrogen produced by renewables present an opportunity to substitute fossil fuel feedstocks in some activities, such as hydrogen reduction in iron and steel making.

Production of hydrogen via renewables

Hydrogen has many uses in the mining industry such as generating high-temperature heat, power, feedstock, fuel for transportation and other mining equipment, and energy storage. Currently, it is largely produced from natural gas, coal, and oil [57]. For mining operations with the capability to install variable renewable energy technologies such as wind and solar, excess electricity could be converted to hydrogen and stored for other mining activities. For example, the Raglan Mine in Canada has been replacing diesel with wind power and energy storage [58].

3.2. Opportunities for mining communities and circular economy

Rapid growth of renewable technologies also presents synergistic opportunities between the mining industry, local and national governments, and renewable technologies, most of the latter of which use materials that are considered critical—i.e., they are of strategic importance to certain industries and have a certain degree of supply chain risk. These include minerals such as cobalt, lithium, nickel, and rare earth metals. For most of these materials, substitution with another metal or mineral is either infeasible or reduces the effectiveness of the technology.

Supply risk for these materials is partly caused by political instability and environmental concerns. Unstable countries contribute a significant amount to mineral production, e.g., 50% of cobalt production comes from the Democratic Republic of Congo [59]. The communities where many mine sites operate are generally rural and agricultural. Sharing renewable energy with communities around mines will stimulate economic activities by encouraging agri-business, which will create jobs, leaving a lasting impact on communities and promoting social and political stability.

A reduction in mining costs (by downsizing energy expenditures) can increase a host country's competitiveness, which, in turn, can encourage more in-country processing operations. This has been strategically important for many mining countries as, at present, most raw minerals are exported to places where lower energy costs and more reliable energy supply render processing more economical [60]. This deprives many countries of the additional value that could be gained from the mineral sector. One of the inhibitors of increasing in-country mineral processing in mining countries is the lack of affordable and reliable energy.

3.3. Options in renewable energy integration

Renewable integration opportunities will require customization depending on the particular mining operation, its location relative to available renewable resources, and on-site energy requirements of the mine. Opportunities across the mining sector consist of new investment and participation from domestic and foreign investors [7]. Increased local content could result if renewable integration draws local investment into the mining sector, creating shared value [61].

We now highlight loads that could benefit from integrating renewables for two types of mining operations: iron and gold, which were selected based on their environmental impact, and the benefits that renewable energy can confer on their greenhouse gas content. Some of the ensuing discussion also applies to other sub-sectors of the mining industry. The disaggregated energy data used in this section – even from reliable sources such as Natural Resource Canada and U.S. benchmarking studies – have several discrepancies [62]. Nevertheless, these data provide valuable insight into average energy consumption; the actual energy consumption by a specific activity and mining company could differ from the average values reported herein.

Iron and Steel Production

Iron and steel production are divided into: ore mining, and iron and steel making, all of which are energy intensive (with a significant amount of this energy sourced from fossil fuels), and consequently generate high greenhouse gas emissions. Several iron mining activities are powered by electricity. Katta et al. [45] indicate that, in 2016, about 39% of the total energy used by Canada's iron ore mining sector came from electricity.

The comminution and pelletization processes consume a significant amount of this electricity per ton. Iron ore production with renewable resources such as solar, wind, and geothermal could produce some of this electricity. Since no change in the mining processing system would be required, renewable electricity could be applied to existing, as well as to new, mining sites. Analysis using tools such as REopt [63] could determine optimal renewable integration based on the mine load profile and location.

Iron ore mining also uses a significant amount of direct fossil fuels [45]. For example, the heavy fuel oil or coke in palletization accounts for about 896,808 BTU/t (≈263 kWh/t) of pellets produced. In 2016, firing activities accounted for about 42% of total energy used by the Canadian iron ore mining sector. Drying also uses a significant amount of fossil fuel, typically diesel, at about 51,856 BTU/t (≈ 15 kWh/t) of material produced. These activities are medium- to high-temperature processes up to 300 °C (for drying) and up to 1350 °C (for pelletizing) [64]. For iron mining sites with availability of sunlight and supporting geology, deep geothermal and concentrated solar power technology could satisfy drying heat demand. Commercially available concentrated solar power cannot completely replace heavy fuel oil and coke use for high-temperature processes but, as mentioned in Section 4, there are promising technologies that can produce heat above 1000 °C. While it is not yet economical to produce hydrogen with renewables at a scale needed by mining operations, hydrogen created with renewable energy could be used to meet demands for high-temperature heat (https://hydrogeneurope.eu/green-heating-and-cooling). Given financial constraints, mining sites with good renewable energy resource availability and high energy costs could exploit excess renewable energy produced during peak hours, which could be used to create hydrogen that can be stored and combusted to generate required heat.

A significant amount of energy in iron and steelmaking is used in process heat. In the United States, these industries comprise about 8% of total energy consumed by the manufacturing industry, and account for about 70% of total energy used by primary metal industries [44]. Most of this is employed directly for process energy (about 35% of total energy used in iron and steelmaking). The United States has made great strides in electrifying steel furnaces by processing scrap. Over 60% of the steel produced in the United States uses an electric arc furnace [65]. However, the bulk of energy used in iron and steelmaking is supplied from natural gas.

There may be limitations on electrifying some iron and steel production loads with renewables, especially for existing operations in primary iron and steel production. Further mining-operation-specific analysis would be needed to determine the economics and technical viability of renewable options, both for new mines or as a way to reduce costs and carbon emissions at existing facilities. For new or future projects, a strong focus on demonstrating recent technology innovations in process electrification that have been applied in other sectors could be explored to expand the applicability of these renewable-energy options. Other fossil-fuel-intensive activities unique to mining, such as digging, drilling, haulage and loading, should be analyzed to better understand the applicability of process electrocution to take advantage of low-cost renewable sources, if available.

Gold Production

Gold production is the most energy- and greenhouse-gas-emission intensive metal per unit produced, and this characteristic is likely to persist with the depletion of high-grade gold reserves. Unlike iron and steel production, which use a large amount of fossil fuels for feedstock processing and process heat, gold production uses a much higher contribution of electricity, presenting more opportunities for renewable integration.

The majority of fossil fuel use stems from underground gold ore extraction [45]. Particularly relevant in underground operations in Canada are activities such as: drilling (roughly 8 kWh/t ore removed); mucking (roughly 6 kWh/t of ore removed); and transportation (6 kWh/t from an underground mine and 113 kWh/t from an open pit mine). Many of these activities can be electrified, allowing for more renewable-based energy sources. Additionally, as the industry extracts more gold from underground reserves, the higher energy intensity of underground mining will further increase energy consumption. Thus, expanded consideration of energy efficiency, paired with renewable integration into material handling in underground mines, are bound to significantly reduce the energy intensity and carbon footprint for gold extraction. In an effort to improve mine air quality, underground mines are already actively engaged in electrifying their activities due to pressure to reduce diesel particulate matter. Mill heating could be powered with renewables in areas with strong resources (e.g., high wind speeds or solar irradiation). Current commercially available renewable technologies may not be able to economically substitute for natural gas in high-temperature processes at the time of this writing, but may be able to do so under the right conditions in the future.

4. Challenges for renewable energy integration in mining

Renewable energy use in the mining industry is growing, but technical challenges still limit the quantity of renewable energy that can serve operational loads. The bulk of the mining industry's energy demand requires careful evaluation when considering renewable integration. This section presents some of these considerations.

4.1. Mining operation-specific challenges

Feedstock Demand

Mining operations that require fossil fuels as a feedstock are usually difficult to fully decarbonize with current renewable technologies. Advancement will allow for higher penetration levels. While biomass (charcoal) can be used as a feedstock alternative in some operations, global sustainable production of charcoal, its transport cost to plant sites, and technicalities of charcoal use in steelmaking are still major concerns [34,66]. Hydrogen also presents an alternative feedstock to fossil fuels in, e.g., direct-reduced iron operations; it presents a much

Table 3
Current commercially available and economical renewable energy technologies.

Category	Technology type	Temperature levels
Renewable source	Biomass, boiler	Low
	Biomass, high temperature	Medium
	Biomass, combined heat-and-power	High
	Biogas, anaerobic digestion	Low
	Solar PV[a]	High
	Wind[a]	High
	Heat pump	Low
	Geothermal direct use	Low
	Deep geothermal	Medium
Energy storage	Solar thermal	N/A
	Hydrogen	N/A
	Pump storage	N/A
	Battery storage	N/A

Note: Low temperature (150 °C), medium temperature (150 °C–400 °C), and high temperature (> 400 ° C). National Renewable Energy Lab estimates supplemented by [44,54,69].

[a]High temperature heat production using solar and wind beyond 550 °C is not yet commercially offered, and is still in the demonstration phase at research facilities.

better source in terms environmental impact than biomass when produced using water and renewable electricity. But generating hydrogen using renewable sources at the required scale is still expensive. More research and development investments are needed to reduce the cost of hydrogen produced by renewables that could be used in metal processing. For example, commercial use of hydrogen as a substitute for carbon monoxide in steel making is not expected until the 2030s [57].

Process Heat Demand

Process heat demand is a major energy consumer within the mining industry. Process heat requirements for the mining industry span the spectrum from low- to high-temperature. Industrial low-temperature heat is defined as below 150 °C; medium-temperature as temperature between 150 °C and 400 °C; and high-temperature above 400 °C [54, 57]. This variability of process heat demand dictates technology selection at the mine site. For example, in steel production, a temperature between 800 °C and 1200 °C is used in the reduction of iron oxide to metallic iron. In the copper smelting process, a heat temperature between 250 °C and 350 °C is used in roasting copper ore to copper oxide. During the aluminum extrusion process, aluminum billets are heated to soft solids at a temperature of between 400 °C and 500 °C. Low- to medium-temperature heat is generally produced through steam, while direct heat (mostly through the combustion of fossil fuels) is used to produce high-temperature heat [54]. Currently, high-temperature industrial requirements are generally fulfilled by fossil fuels — 65% using coal, 20% with natural gas, and 10% through oil [54,57].

Table 3 shows that most renewable energy technologies currently deliver low- or medium-temperature process heat and are thus only applicable for some process requirements. Concentrated solar power technology is showing promising results but requires larger land availability and sufficient solar resources. Currently, commercial applications of concentrated solar power can achieve process heat temperatures of up to 550 °C [36]. However, experimental concentrated solar power facilities, such as the Heliogen Lancaster California facility, have demonstrated temperatures in excess of 1000 °C [67]. Researchers at the Barbara Hardy Institute have developed a technique that could help lower this fossil fuel dependency in high-temperature process heat production. Through their pilot system, they demonstrated that renewable energy from hybrid systems (solar and wind energy, coupled with thermal energy storage) could deliver industrial temperatures between 150 °C and 700 °C [68]. This could serve the demand for many metal processing activities that require medium- to high-temperatures, such as non-ferrous metal production involved in copper smelting and aluminum extrusion.

At the time of this writing, the only commercially available renewable solution for high-temperature process heat in excess of 550 °C can be delivered by biomass (charcoal or combined heat and power). Charcoal can generate heat temperature of up to about 1260 °C [70]. But, biomass fuel sources such as charcoal or wood are not without limitations. Hydrogen produced by renewables might meet high-temperature heat requirements, but currently production of hydrogen using renewables is largely uneconomical [57]. Hydrogen is also an attractive emissions-free source of energy for several other mining activities [71, 72].

Constant Energy Demand

Mining operations require significant, high-quality and generally constant energy supply, often 24 h a day and seven days a week, that can only be met by few renewable sources (hydro-electric and geothermal). However, hydro-electric and geothermal are limited because they have to co-occur with mineral resources to be applicable; the need to meet constant energy demand therefore still poses challenges associated with their implementation and presents a barrier when attempting to integrate large shares of variable renewable energy. Even technologies such as wind and solar whose co-occurrence may be more favorable could overproduce during peak generation hours; this can lead to complexities associated with the excess energy, some of which may be stored using, e.g., batteries or hydrogen electrolysis. If the mine is grid-connected and has a net metering or grid export agreement with the system operator, it may be able to sell the excess energy. However, most commonly, extra energy is curtailed, because current battery technologies are limited in their number of hours of storage, and a larger battery bank could be economically prohibitive. Moreover, net metering or some other export compensation mechanism can be difficult for mining projects to obtain for a variety of reasons, including: lack of regulatory framework allowing for grid exports; size limitations in jurisdictions where net metering is available; and low compensation rates.

To manage variability, mines often turn to hybrid systems generally supported by on-site diesel generators, which reduce fossil fuel use but do not eliminate it entirely. Examples include solar PV-battery-diesel hybrid systems, wind-battery-diesel hybrid systems, and solar-wind-battery-diesel systems. For example, the mining town of Coober Pedy in Australia operates a hybrid wind (4 MW), solar (1 MW), and battery storage (1 MW/500 kWh) powerpack that has displaced about 70% of diesel use [7]. Many mines can only economically integrate renewables to cover part of their load, for example, between 30% and 40% of total electricity demand — using current renewable and control technologies [73].

Another approach to address variability and reduce the capital investment for renewable energy is to ensure the mining operation is energy-efficient. In particular, the electric load is an important aspect of planning optimal generation capacity for renewables [74]. The literature contains several recent reviews of energy efficiency best practices in the mining industry [9,10], which can help reduce the overall and renewable energy needs, thus reducing capital investments. These practices include mine-to-mill optimization [75], ventilation on demand [76], thermal management for energy efficiency of haul trucks [77], and use of control algorithms to optimize energy demand [78,79].

Although the use of renewable energy technology can clearly reduce the need for carbon-based energy at mines—especially those with exceptional renewable resources such as wind, hydropower or solar, or with high energy cost, over the near term, it is not likely to provide deep decarbonization of mining operations. Continued efforts to further lower the cost of renewable power and energy storage, combined with the expansion of mine operators' ability to effectively address the integration of variable energy generation, will be needed.

Mining Industry Design and Investment Structure

Most mining operations make investment decisions that account for the life of the mine, which may range from 2 to more than

50 years. This time horizon is a critical input into the mine's return-on-investment calculation [80]. Major decisions in mine planning and design are usually made during the pre-feasibility and feasibility phases. Once the mine site is constructed according to a design, the selected technologies and their capacities are fixed for several decades. Making changes to the mine development plan after the investment decision has been made can require many levels of approval and may cause ripple effects on the design.

Most mining production activities are based on an all-or-nothing approach, meaning that the mine produces at capacity as long as it is covering its operational expenditures, because it has already incurred the capital investment. Once a mine has the ability to change its capital investment for expansion, there is room for flexibility. This feature of mining operations has implications in integrating renewable energy. For example, the blast furnace-basic oxygen furnace mechanism in steel manufacturing accounts for around 70% of global steel production. Many of the processing plants utilizing this technology were built in the past 10 to 20 years and have a long lifespan, and it would be costly to integrate renewable energy into their existing operations before the end of their design life [66]. In this case, other solutions such as CO_2 abatement or energy efficiency could be more appropriate [66]. At the time of this writing, CO_2 abatement technologies are still costly, but if research and development enable cost reduction, blast furnace-basic oxygen furnace technology could benefit. Renewable energy may be competitive economically when installed as part of a mine expansion or when planning new operations (i.e., if renewable energy solutions are evaluated as part of the design and feasibility study processes). At a workshop held for mining stakeholders at the National Renewable Energy Laboratory in 2019, participants identified a lack of training and education resources for mine engineers to evaluate renewable energy as part of overall mine design. This is a gap that mining schools and engineering programs could address with updates to their curricula. It could also be an opportunity for professional training and certification organizations. For example, Oz Minerals and Cassini Resources from Australia through their pre-feasibility study indicated that their proposed new copper-nickel mine located in West Musgrave, Australia will be powered by up to 80% renewables. The companies propose to utilize a hybrid system of solar-wind-battery-diesel which produces 220,000 tons per annum less CO_2 compared to a fully diesel-powered operation [81].

4.2. Industrial linkage challenges

Despite renewable potential (see Section 3), the ratio of renewable-to-total energy used in the mining industry is still small [31]. Discussions with mining industry professionals and related stakeholders regarding the opportunities for and barriers to deployment of renewable energy technologies at mine sites elicited the challenges presented in this section and the potential solutions identified in Section 5 [82].

Political Will and Adjustment Costs

Integrating more renewable energy into mining operations will cause resource relocation from fossil fuels to renewable energy and will result in displacement effects (job losses and re-alignment of skills within the broader energy economy). This is especially true for countries where the mining sector is a significant portion of the energy demand. In such economies, increasing the percentage of renewable generation in the mining sector will displace significant resources from the fossil fuel supply chain to the renewable energy supply chain. Depending on the country, the domestic fossil fuel supply chain might be a more dominant portion of the economy than the renewable energy supply chain (which might rely more on imports). In such cases, the political will does not exist to provide the policies and infrastructure for a transition to renewable energy in the mining sector.

In our discussions with industry, one participant from a company with mines in Africa relayed a relevant experience that illustrates this point. They own and operate a mine in a country with an unreliable energy generation system that is heavily reliant on natural gas-fired plants. In a particular period of load shedding, the mining company engaged the government in discussions to evaluate increasing the mine's renewable generation capacity to remove some of their load from the grid. Fearing the loss of a major customer who pays on time, the state-owned utility preferred the mining company to provide them support to acquire natural gas feedstock to maintain viability of their existing operations.

Conflicting Business Models

Principal among the challenges is the misalignment in commercial incentives between the mining and energy industries. Because of cycles in commodity prices, the mining industry values flexibility, or the ability to ramp down or cease production at a mine site if the metal market price becomes unprofitable to keep the mine open. However, of the high capital costs for renewable energy, renewable energy power purchase agreements are typically longer term in nature.

There can also be misalignment between mine life and renewable asset life. Most mining projects evaluate profitability of a mine project to the end of its estimated life (which can range from 2 to more than 50 years), while renewable project payoffs might correspond to a minimum of 8 years. This mismatch in asset life makes negotiating cost-effective renewable energy contracts difficult. Many renewable projects associated with the mining industry are, accordingly, owned by mining operators. However, in our conversations with industry, several companies indicate that their core business is mining, not energy generation. Favorable contractual arrangements could help scale renewable integration beyond what mining companies are capable of installing and managing by themselves. Also, some countries' host policies do not support favorable business models for renewable integration in that they lack the legal framework for net-metering policies to export excess energy to the grid, or for renewable project ownership transfers post-mining.

Need for Technology Proof-of-Concepts

The growing renewable energy industry has largely been focused on electricity production and grid integration over the last decade, and technology solutions designed for other industrial processes are still nascent. While wind, solar and other renewable technologies have established solid track records, there is limited experience in their integration into the on-grid and off-grid mining sectors. Other energy service technologies, such as expanding energy storage and advanced control markets, are becoming more common within the utility sector; however, the associated technical and financial models are still largely untested within the mining industry. Other truly emerging technologies such as hydrogen mobility and fuel cells for power production and resiliency have limited commercial histories. For off-grid mines, which likely have some of the highest potential for renewable energy deployments due to the traditionally high cost of energy services, incorporating larger contributions of variable renewable technology, while demonstrated in smaller commercial and utility applications, have not been widely demonstrated at scale within the mining sector. While a few larger companies have run pilots to demonstrate economic viability of these technologies, they remain out of reach for mid-market and small-scale mining operations without analytical and financial support.

Lack of Renewable Energy Awareness and Expertise

Decision makers in both the private sector and within some governments do not often consider renewable solutions during mine planning, negotiation, and design. Stakeholders indicate that the engineers who determine a mine's design are unequipped with the skillsets and detailed information to incorporate renewable energy into their analyses. Governments and regulators in many countries where mining comprises an appreciable portion of gross domestic product also do not have experience in incorporating renewables into their power system, again limiting the abilities of mines to access renewable energy though power

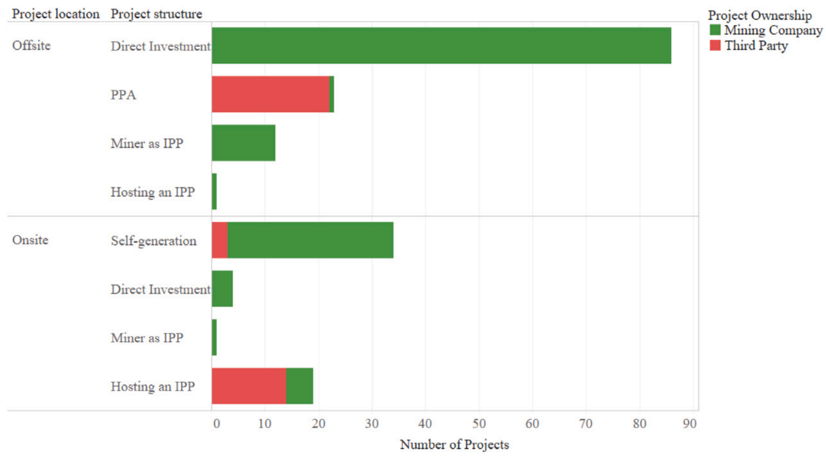

Fig. 4. Renewable Project Business model. PPA: power purchase agreement; IPP: independent power producers.
Source: Data is from [31].

purchase contracts. Mining and energy policies, development agreements, and evaluation tools are generally not created with renewable energy in mind. Additionally, fossil subsidies, special tax conditions and fuel levy exemptions granted to mines through mining agreements can inhibit the use of alternative energy sources.

Land Constraints

Another impediment that the mining industry faces is the availability of land on which to site renewable energy assets. Mining companies point to a general misconception about the footprint of mine sites, and how little of the terrain is of suitable grade and ground cover for solar PV or wind turbine installation. Also, suitable land for renewable projects could be the same land that has mineral potential (i.e., to host mineral resources and reserves or that have significant exploration potential).

5. Enabling approaches

Joint Institute for Strategic Energy Analysis' conversations with mining stakeholders revealed a pervasive and growing interest in renewable integration within the mining industry. The workshop was held under the Chatham House rule [83]; thus, we are unable to ascribe opinions to particular individuals or their affiliations. This section presents enabling approaches that could help with scaling this integration.

5.1. Alignment of business model and incentives

Some mining companies are currently executing power purchase agreements with renewable projects, and self-finance, regardless of the challenges with mismatched commercial incentives. However, many mining companies, especially small- to medium-size operations, are still wary of the lack of flexibility renewable energy options present, and/or lack the funding needed for initial investment. Policy support will be important in developing contract structures (such as power purchase agreements) that better align incentives and regulatory frameworks that support net metering for grid-connected mining operations. Conducting analysis of costs and benefits of integrating renewables could be used to inform respective governments and other stakeholders, such as the financial sector, which provide funding to these projects. The task to engage the energy and mining industries in developing these suitable power purchase agreements can be facilitated by host governments that have the most to gain in terms of stimulating local economies, increasing tax revenues, and achieving greenhouse gas emissions goals, among other benefits.

5.2. Capacity building

As discussed in Section 4, there are several technical considerations for integrating renewable sources into mining operations, many of which will need to be tailored to specific mine needs. Access to existing tools, integration, and training to assess renewable integration potential during a pre-feasibility phase will be important to expand renewable energy development, especially for small- to medium-size companies and their consultancies. These capabilities can also be provided through renewable energy developers, third-party independent engineers or research institutions. Additionally, educational programs at colleges and universities, and professional certifications, should be used to address this knowledge gap. For single-technology applications, solar has the highest installed capacity, followed by wind energy. The majority of these projects – around 85% – are owned by mining companies. The remaining 15% are either contracted through power purchase agreements or other means by which the mining company is an off-taker (see Fig. 4). Approximately 73% of these projects are off-site while 27% are on-site.

5.3. Research and development

More research and development are required to incrementally remove today's barriers to integrating renewables into mining operations. The mining industry needs cost-effective solutions for scaling renewable use, for using renewable sources to produce high-temperature heat, and for implementing low-cost energy storage with longer durations. There are also research and development opportunities for other emerging solutions such as green hydrogen production as alternative low-emissions feedstocks or for heating. Similarly, there are opportunities to electrify transportation (for equipment that is currently powered by diesel) and to improve the energy efficiency of material haulage (e.g., energy recovery on downhill transportation). Research and development investments for the mining industry can have second-order benefits in terms of advancing solutions for other energy-intensive industries, including chemicals and food processing. Progress has been made within the utility sector to incorporate large amounts of renewable energy while expanding general electrification of the energy sector. The mining industry does not need to lead the efforts in renewable energy adoption but can realize significant gains in renewable energy use by adopting technologies and techniques that have been deployed successfully in other sectors.

5.4. Pooling resources

The availability of capital is a major obstacle to scaling renewables in places where favorable power purchase agreements may not exist. Many mining activities are located in close proximity to other producers (e.g., processing facilities) and local communities. Pooling resources between these parties can allow for the installation of a shared system that serves local energy needs. This could be a viable solution, especially for small- to medium-scale mine sites with limited capital availability.

Especially for off-grid or edge-of-grid applications, there is an expanded opportunity to employ multi-technology microgrid systems, which can confer resiliency. There are, however, notable challenges with productive uses for microgrids in remote communities [84]. Mining companies already invest internationally, such as in operations in Sub-Saharan Africa, and in independent power producers or the grid [85]; the same investment model could be used to acquire a multi-technology microgrid that can shared. A mine site could act as an anchor customer to such a microgrid and local communities could benefit from an additional, reliable source of energy (provided that the community and mine site are in close enough proximity to minimize wiring costs). Policy and regulations are often critical in facilitating microgrids, so engagement with governments is important.

5.5. Government policies and regulations

As with microgrids, government policies and regulations are central to many enabling approaches. At a global level, increasing coordination and cooperation help to deploy renewable energy technologies, but these implementation efforts can be stalled at the county and local levels. In most resource-rich countries, existing policies and regulations were not created with renewable sources in mind. It is only recently that some of these countries have begun reviewing their policies and regulations to help scale the development of renewable resources, but often these do not explicitly address the concerns of the mining industry.

Additionally, in many developing countries, policies require companies to source a certain percentage of intermediate goods from domestic manufacturers [86]. Manufacturing is an energy-intensive sector, and many of these developing countries have limited access to energy, and/or have unreliable energy generation. Renewable energy could be used to support low-energy-intensive manufacturing such as agribusiness and could offer countries opportunities to reap the benefits of their local contacts to fulfill local content requirements. The collaborative efforts between the mining industry, the energy industry, international organizations, and host governments will be needed to create policy and regulation to support scaling renewables. For example, large systems could be installed that can be shared between miners and communities.

To assist mines specifically in accessing renewables, governments may need to review their tax exemptions and subsidies that currently apply to fossil fuel purchases, or to explore the possibility for carbon pricing or renewable energy portfolio standards (which can create tradable renewable energy certificates). Research and documentation of mechanisms by which governments have traditionally had a significant impact on their renewable energy policy goals and how they would apply to renewable energy would also be useful. For example, government policies can help in innovating green hydrogen technologies, stimulating commercial demand, building infrastructure, and reducing costs through funding, among other actions [57].

6. Conclusions

The mining industry is not only one of the most energy-intensive industries, it is also the major source of raw materials for several industries including renewable energy technologies. The demand for raw materials will increase as many low-income economies shift to middle-income status; correspondingly, the pressure on the mining industry to reduce emissions will intensify. Because of their energy consumption, mining operations are also sensitive to energy costs and their variability. Cost reductions of wind and solar PV technologies provide strong financial incentives to expand the use of renewable energy within the mining industry. Many options reduce carbon production and take advantage of energy cost savings, such as an increase in energy efficiency measures, expanded use of energy recovery, and the use of renewable energy to supply electric, transportation and thermal energy needs. These renewable-energy options are not without challenges and, therefore, remain relatively unexplored across the mining sector. We present here the challenges, opportunities, and enabling approaches for renewable use in mining operations. The viability of different energy sourcing options is also greatly dependent on where the mine is located and whether it receives power from an external source or by self-generation. Additionally, the phase of its development, construction and operation will have a major impact on the viability of incorporating different renewable or energy efficiency options.

Renewable energy can be integrated into the extraction, processing, and refining phases of mineral production. These activities include, but are not limited to, transportation, drilling, digging, loading, and power generation for mine sites without grid connection. For mines that are grid-connected, working with the utility to expand the use of renewable energy either on the utility or mine side of the utility meter could provide benefits of renewable technologies, while potentially sheltering mines from some of the more complicated legal and financial concerns of developing their own renewable energy sources. Renewable energy can also be used to provide process heat, though most current sources are best aligned to provide low- or medium-value heat (below 400 °C).

While many activities are common across the mining industry, energy requirements vary. We use iron ore extraction and gold production to showcase different opportunities. Both commodities use a significant amount of electricity that could be decarbonized by renewable sources. Unlike gold production, iron and steel production use fossil fuels as direct-process feedstock or to make heat. An environmentally-friendly solution for iron and steel will require more than the use of renewables if deep decarbonization is to be achieved. Despite numerous opportunities, technical issues will need to be considered. The incorporation of small contributions of renewable energy for electricity production in isolation or on the utility side of the mine meter are not technically challenging. The implementation of energy efficiency efforts to transition fossil-based energy uses to electricity can also allow for expansion of renewable energy in the mining sector. Expanding the contribution of renewable energy, especially for electrically isolated mines, poses additional technical issues that may be specific to the mineral type as well as to the mine, and, thus, will require a more tailored approach. Some of the major technical issues are feedstock replacement, process heat demand, and renewable energy variability. Some mining activities require fossil fuel as inputs either to create carbon or hydrogen for their processes. Biomass and hydrogen present themselves as environmentally-friendly energy sources that can be used as feedstock, though the sustainable production of biomass at a scale required by the mining industry will be difficult. Some mining activities require very high-temperature process heat that is generally not currently attainable by most common renewable sources. While current concentrated solar power, wind, and solar PV technology can provide cost-effective thermal energy in favorable renewable energy resource areas above 400 °C, most high-temperature-energy-intensive mining activities require temperatures beyond those achieved by current commercially available concentrated solar power. The use of wind and solar energy systems for high-temperature thermal energy, although technically viable, is not currently commercially available. While variability of renewable energy is seen as a challenge to mining operations, hybrid systems can help alleviate this, especially when combined with energy storage and fossil-based dispatchable generation. Although not technical or financially viable to provide all of the mines' energy needs using green sources, mines can greatly expand their use of renewable energy using commercially existing technologies.

Despite the technical and financial challenges, there are solutions that can be employed to enable scaling of renewables in the mining industry. The first solution is alignment of a business model between the energy (utility, renewable and financing) and mining industries, which could be facilitated by host governments or other legal entities. Second, capacity building, in terms of improved tools and educational programs, could be developed to increase the skills of key stakeholders in the mining industry. Third, greatly expanded information sharing and the development of pilot projects within the mining sector will help transfer knowledge of how renewable energy at lower energy contributions can be successfully implemented. Benefits from these experiences will also extend to other energy-intensive industries such as the chemical industry. Fourth, government policy and regulations can play an important role in implementing many of the approaches we suggest. For example, most basic research and development is initiated at government research institutes. Additionally, government support in aligning policies across industries and advocating for integration of renewable energy sources in adjacent sectors, such as the utility sector, could help both government and mining companies achieve emissions goals, which have been one of the central issues in many developing, resource-rich countries. Finally, and especially when considering longer term deep decarbonization methods and impending cost reductions of renewable technologies, expanded research and development will be crucial to addressing many of the remaining technical issues to further transition the mining industry away from fossil fuels. For example, finding ways to economically achieve high-temperature requirements by renewable sources, and determining alternative and sustainable feedstock will be important to many energy-intensive mining activities. Other enabling approaches include pooling of resources between mines and communities.

This paper provides insights into the potential of renewable use in the mining industry. However, mining processes vary depending on the type of mineral produced and the possibilities for renewable resources at the mine site. Further research could focus on identifying specific opportunities, technologies, and implementation strategies across the value chain of a variety of minerals with similar operational procedures. Specific attention should be placed on minerals or processes that could benefit from renewable energy technologies in terms of the reduction in energy use and emissions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments and disclaimer

This work was authored, in part, by the National Renewable Energy Laboratory, United States, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding was provided by the Joint Institute for Strategic Energy Analysis (JISEA), United States. Sections of this paper were previously published as a technical report https://www.nrel.gov/docs/fy20osti/76156.pdf. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

References

[1] MIT. Strategic metals: Will future supply be able to meet future demand? 2016, URL https://web.mit.edu/12.000/www/m2016/finalwebsite/problems/supplydemand.html, Accessed August 27, 2020.
[2] Norgate T, Haque N. Energy and greenhouse gas impacts of mining and mineral processing operations. J. Cleaner Prod. 2010;18(3):266–74.
[3] Lezak S, Cannon C, Blank K. Low-Carbon Metals for a Low-Carbon World: A New Energy Paradigm for Mines. Tech. Rep., Rocky Mountain Institute; 2019.
[4] Carvalho FP. Mining industry and sustainable development: Time for change. Food Energy Secur 2017;6(2):61–77.
[5] Kirk T, Cannon C. Sunshine for mines: A brighter vision for sustainable resources. 2020, URL https://rmi.org/sunshine-for-mines-a-brighter-vision-for-sustainable-resources/, Accessed August 27, 2020.
[6] Igogo T, Lowder T, Engel-Cox J, Newman A, Awuah-Offei K. Integrating Clean Energy in Mining Operations: Opportunities, Challenges, and Enabling Approaches. Tech. Rep., National Renewable Energy Laboratory; 2020.
[7] Maennling N, Toledano P. The renewable power of the mine. 2018.
[8] Larsen N. Favorable renewable-energy economics are now too attractive to ignore. 2019, URL https://internationalbanker.com/brokerage/favourable-renewable-energy-economics-are-now-too-attractive-to-ignore/, Accessed August 27, 2020.
[9] Levesque M, Millar D, Paraszczak J. Energy and mining–the home truths. J Cleaner Prod 2014;84:233–55.
[10] Awuah-Offei K. Energy efficiency in mining: A review with emphasis on the role of operators in loading and hauling operations. J. Cleaner Prod. 2016;117:89–97.
[11] U S Department of Energy. Mining industry energy bandwidth study. 2007, URL https://www.energy.gov/sites/prod/files/2013/11/f4/mining_bandwidth.pdf, Accessed August 27, 2020.
[12] Oladiran M, Meyer J. Energy and exergy analyses of energy consumptions in the industrial sector in South Africa. Appl. Energy 2007;84(10):1056–67.
[13] Imasiku K, Thomas VM. The mining and technology industries as catalysts for sustainable energy development. Sustainability 2020;12(24):1–13.
[14] Ditsele O, Awuah-Offei K. Effect of mine characteristics on life cycle impacts of US surface coal mining. Int J Life Cycle Assess 2012;17(3):287–94.
[15] Norgate T, Haque N. Energy and greenhouse gas impacts of mining and mineral processing operations. J. Cleaner Prod. 2010;18(3):266–74.
[16] Kuykendall T. Path to net zero: Miners are starting to decarbonize as investor pressure mounts. 2020, URL https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/path-to-net-zero-miners-are-starting-to-decarbonize-as-investor-pressure-mounts-59583837, Accessed September 1, 2020.
[17] ICMM statement on climate change. 2015, URL https://www.icmm.com/website/publications/pdfs/climate-change/icmm-statement-on-climate-change-2015.pdf, Accessed August 27, 2020.
[18] The growing role of minerals and metals for a low carbon future (No. 117581, pp. 1-0). The World Bank; 2017.
[19] Hodgkinson JH, Smith MH. Climate change and sustainability as drivers for the next mining and metals boom: The need for climate-smart mining and recycling. Resour. Policy 2018;101205.
[20] Zharan K, Bongaerts JC. Decision-making on the integration of renewable energy in the mining industry: A case studies analysis, a cost analysis and a SWOT analysis. J Sustain Mining 2017;16(4):162–70.
[21] Moreno-Leiva S, Haas J, Junne T, Valencia F, Godin H, Kracht W, Nowak W, Eltrop L. Renewable energy in copper production: A review on systems design and methodological approaches. J. Cleaner Prod. 2020;246:118978.
[22] Paraszczak J, Fytas K. Renewable energy sources–a promising opportunity for remote mine sites? In: Proceedings of the International Conference on Renewable Energies and Power Quality, 2012; p. 28–30.
[23] Soberanis ME, Alnaggar A, Mérida W. The economic feasibility of renewable energy for off-grid mining deployment. Extractive Ind Soc 2015;2(3):509–18.
[24] Stegen KS. Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis. Energy Policy 2015;79:1–8.
[25] Dutta T, Kim K-H, Uchimiya M, Kwon EE, Jeon B-H, Deep A, Yun S-T. Global demand for rare earth resources and strategies for green mining. Environ. Res. 2016;150:182–90.
[26] Baker L. Renewable energy in South Africa's minerals-energy complex: A 'low carbon' transition? Rev African Polit Economy 2015;42(144):245–61.
[27] Furnaro A. Neoliberal energy transitions: The renewable energy boom in the Chilean mining economy. Environ Plan E: Nat Space 2019;951–75.
[28] Votteler RG, Brent AC. A literature review on the potential of renewable electricity sources for mining operations in South Africa. J Energy Southern Africa 2016;27(2):1–21.
[29] McLellan B, Corder G, Giurco D, Ishihara K. Renewable energy in the minerals industry: A review of global potential. J. Cleaner Prod. 2012;32:32–44.
[30] Zharan K, Bongaerts JC. Survey on integrating of renewable energy into the mining industry. J Environ Account Manage 2018;6(2):149–65.
[31] BNEF. Miners turn to clean energy: Costs and key strategies. Database. 2019.
[32] World mining database. 2020, URL https://www.world-mining-data.info/?, Accessed August 27, 2020.

[33] Norgate T, Jahanshahi S, Rankin W. Assessing the environmental impact of metal production processes. J. Cleaner Prod. 2007;15(8–9):838–48.
[34] Norgate T, Haque N, Somerville M, Jahanshahi S. Biomass as a source of renewable carbon for iron and steelmaking. ISIJ Int 2012;52(8):1472–81.
[35] Global metals & mining. 2021, URL marketresearch.com, Accessed February 14.
[36] Ericson S, Engel-Cox J, Arent D. Approaches for Integrating Renewable Energy Technologies in Oil and Gas Operations. Tech. Rep., National Renewable Energy Laboratory; 2019.
[37] World Steel Association. World steel in figures 2019. 2019, URL https://www.worldsteel.org/en/dam/jcr:96d7a585-e6b2-4d63-b943-4cd9ab621a91/World%2520Steel%2520in%2520Figures%25202019.pdf, Accessed September 1, 2020.
[38] Alova G. Integrating renewables in mining: Review of business models and policy implications. 2018, p. 14.
[39] Sahu H, Prakash N, Jayanthu S. Underground mining for meeting environmental concerns–a strategic approach for sustainable mining in future. Procedia Earth Planet Sci 2015;11:232–41.
[40] Davy A. It's time for the mining industry to step up on the environment and human rights. 2018, URL https://www.ethicalcorp.com/content/its-time-mining-industry-step-environment-and-human-rights, Accessed September 1, 2020.
[41] Norton Rose Fulbright. Renewable energy in Latin America. 2017, URL https://www.nortonrosefulbright.com/-/media/files/nrf/nrfweb/imported/renewable-energy-in-latin-america.pdf?la=en&revision=66edb636-af27-43d7-8c44-c65564b1833b, Accessed August 27, 2020.
[42] Natural Resources Canada. Government of Canada promotes renewable energy innovation in mining. 2019, URL https://www.canada.ca/en/natural-resources-canada/news/2019/01/government-of-canada-promotes-renewable-energy-innovation-in-mining.html, Accessed August 27, 2020.
[43] Lazard. Levelized cost of energy and levelized cost of storage. 2019, URL https://www.lazard.com/perspective/lcoe2019, Accessed August 27, 2020.
[44] Energy Information Administration. Manufacturing energy consumption survey. 2014, URL https://www.eia.gov/consumption/manufacturing/data/2014/#r5, Accessed August 27, 2020.
[45] Katta AK, Davis M, Kumar A. Development of disaggregated energy use and greenhouse gas emission footprints in Canada's iron, gold, and potash mining sectors. Resour. Conserv. Recy. 2020;152:104485.
[46] Palchack D, Cochran J, Ehlen A, McBennett B, Milligan M, Chernyakhovskiy I, Deshmukh R, Abhyankar N, Soonee K, Narasimhan S, Joshi M, Sreedharan P. Gerening the grid: Pathways to integrate 175 gigawatts of renewable energy into India's electric grid, vol. I—National study. Greening the grid program. 2017, URL https://www.nrel.gov/docs/fy17osti/68530.pdf, Accessed August 27, 2020.
[47] Deign J. Mining giants embrace renewables, but decarbonization remains a steep climb. 2020, URL https://www.greentechmedia.com/articles/read/mining-giants-embrace-renewables-but-decarbonization-remains-a-steep-climb, Accessed August 28, 2020.
[48] Booth M, Bixley P. Geothermal development in Papua New Guinea: A country update report: 2000 – 2005. 2005, URL https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0136.pdf, Accessed August 27, 2020.
[49] Judd E. Raglan mine: Canada's first industrial-scale wind and energy storage facility, energy and mines. 2014, URL https://energyandmines.com/wp-content/uploads/2014/08/Raglan.pdf, Accessed August 27, 2020.
[50] Slavin A. First solar PV and battery plant to be built in Australia, BHP partners up, energy and mines. 2016, URL https://energyandmines.com/2016/09/first-solar-pv-and-battery-plant-to-be-build-in-australia-bhp-partners-up/, Accessed August 27, 2020.
[51] Demirel N. Energy-efficient mine ventilation practices. In: Energy Efficiency in the Minerals Industry. Springer; 2018, p. 287–99.
[52] Terblanche PJ, Kearney MP, Hearn CS, Knights PF. Technology selection and sizing of on-board energy recovery systems to reduce fuel consumption of diesel-electric mine haul trucks. In: Energy Efficiency in the Minerals Industry. Springer; 2018, p. 301–33.
[53] Terblanche PJ, Kearney MP, Nehring M, Knights PF. Potential of on-board energy recovery systems to reduce haulage costs over the life of a deep surface mine. Mining Technol 2019;128(1):51–64.
[54] IRENA. A background paper to "renewable energy in manufacturing". 2015.
[55] World Steel Association. World steel in figures. 2019, URL https://www.worldsteel.org/en/dam/jcr:96d7a585-e6b2-4d63-b943-4cd9ab621a91/World%2520Steel%2520in%2520Figures%25202019.pdf, Accessed September 1, 2020.
[56] MIDREX. The MIDREX process - the world's most reliable and productive direct reduction technology. 2018, URL https://www.midrex.com/wp-content/uploads/MIdrex_Process_Brochure_4-12-18.pdf, Accessed August 27, 2020.
[57] IEA. The future of hydrogen: Seizing today's opportunities. 2019, URL https://webstore.iea.org/the-future-of-hydrogen.
[58] Hatch. Raglan mine integrated wind-storage-diesel energy. 2020, URL https://www.hatch.com/en/Projects/Energy/Raglan-Mine-Integrated-Wind-Storage-Diesel-Energy-Project, Accessed August 14, 2020.
[59] Patterson S, Wexler A. Despite cleanup vows, smartphones and electric cars still keep miners digging by hand in Congo. 2018, URL https://www.wsj.com/articles/smartphones-electric-cars-keep-miners-digging-by-hand-in-congo-1536835334, Accessed August 27, 2020.
[60] U N Comtrade. Trade database. 2020, URL https://comtrade.un.org/data/, Accessed August 27, 2020.
[61] Porter M, Kramer M. Creating shared value. Harv. Bus. Rev. 2011;89(1/2):62–77.
[62] Levesque M, Millar D, Paraszczak J. Energy and mining–the home truths. J. Cleaner Prod. 2014;84:233–55.
[63] Ogunmodede O, Anderson K, Cutler D, Newman A. Optimizing design and dispatch of a renewable energy system. Appl. Energy 2021;accepted.
[64] de Moraes SL, de Lima JRB, Ribeiro R. Iron ore pelletizing process: An overview. 2019, Accessed August 27, 2020.
[65] Steel industry profile. 2020, URL https://www.energy.gov/eere/amo/steel-industry-profile, Accessed August 27, 2020.
[66] Decarbonization of industrial sectors: The next frontier. 2018.
[67] CSP startup heliogen cranks up solar thermal to 1,000 degrees. 2020, URL https://www.greentechmedia.com/articles/read/heliogen-cranks-solar-thermal-up-to-1000-degrees-cel.
[68] Jacob R, Belusko M, Liu M, Saman W, Bruno F. Using renewables coupled with thermal energy storage to reduce natural gas consumption in higher temperature commercial/industrial applications. Renew. Energy 2019;131:1035–46.
[69] Renewable energy solution for industrial heat application. 2019.
[70] Cheng Z, Yang J, Zhou L, Liu Y, Wang Q. Characteristics of charcoal combustion and its effects on iron-ore sintering performance. Appl. Energy 2016;161:364–74.
[71] Jackson C, Molloy P. A renewable hydrogen way forward for the mining industry? 2018, URL https://rmi.org/a-renewable-hydrogen-way-forward-for-the-mining-industry/, Accessed August 27, 2020.
[72] Zakharia N. Mining heavyweights form green hydrogen consortium. 2020, URL https://www.australianmining.com.au/news/mining-heavyweights-form-green-hydrogen-consortium/, Accessed August 27, 2020.
[73] Guilbaud J. Hybrid power opportunities in mining. 2019.
[74] Aslam S, Herodotou H, Mohsin SM, Javaid N, Ashraf N, Aslam S. A survey on deep learning methods for power load and renewable energy forecasting in smart microgrids. Renew. Sustain. Energy Rev. 2021;144:110992.
[75] Kojovic T, Thornton D, Adel G, Demeyer S, et al. Can mine to mill optimisation succeed under complex constraints? Australasian Inst Mining Metall Publ Series 2007;105–18.
[76] Chatterjee A, Zhang L, Xia X. Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff. Appl. Energy 2015;146:65–73.
[77] Nessim W, Zhang FJ, Zhao CL, Zhu ZX. Optimizing operational performance of diesel mining truck using thermal management. In: Advanced Materials Research, Vol. 813. Trans Tech Publ; 2013, p. 273–7.
[78] Middelberg A, Zhang J, Xia X. An optimal control model for load shifting–with application in the energy management of a colliery. Appl. Energy 2009;86(7–8):1266–73.
[79] Ristić L, Bebić M, Jevtić D, Mihailović I, Štatkić S, Rašić N, Jeftenić B. Fuzzy speed control of belt conveyor system to improve energy efficiency. In: 2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC). IEEE; 2012, p. DS2a–9.
[80] Statista. Duration of the extraction period of a mine by selected commodities. 2020, URL https://www.statista.com/statistics/255479/mine-life-per-commodity/#::text=, Accessed August 27, 2020.
[81] Spence A. New $1 Billion mine looks to solar, wind, batteries for 80% of power needs. 2020, URL https://reneweconomy.com.au/new-1-billion-mine-looks-to-solar-wind-batteries-for-80-of-power-needs-90179/, Accessed August 27, 2020.
[82] JISEA Workshop with mining industry professionals, november 7, 2019. National Renewable Energy Lab; 2019.
[83] Severn A. The Chatham House Rule. Morecambe Bay Med J 2015;7:87.
[84] Booth S, Li X, Baring-Gould I, Kollanyi D, Bharadwaj A, Weston P. Productive use of energy in African micro-grids: Technical and business considerations. 2018, URL https://www.nrel.gov/docs/fy18osti/71663.pdf, Accessed August 27, 2020.
[85] World Bank. Africa – power mining projects database. 2014, URL https://datacatalog.worldbank.org/dataset/africa-powermining-projects-database-2014, Accessed August 27, 2020.
[86] Stephenson M. Addressing local content requirements: Current challenges and future opportunities. 2013, URL https://www.ictsd.org/bridges-news/biores/news/addressing-local-content-requirements-current-challenges-and-future#::text=.