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Renewable Energy in the Minerals Sector: Assessing Opportunities for Africa

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Abstract

Renewable energy (RE) is becoming an increasingly visible component of the global energy supply mix. As a large consumer of power globally, the mining industry has historically relied on grid power or diesel generators for remote sites. While there is a range of RE technologies, wind power and solar power (particularly that generated by photovoltaic panels) are most prominent in current mining applications. The intermittent nature of RE production makes it ill-suited to the continuous power demand of mining operations without the use of hybrid systems and/or energy storage. There is general clarity on the environmental benefits of using RE, especially as far as reduced emissions are concerned, but it has been assumed that the cost of adopting these technologies is prohibitive. However, the data challenges this assumption and shows that RE is frequently an affordable option. RE is a higher capex/lower opex system relative to grid power or diesel generators. The lifespan of RE installations is currently in excess of 20 years, which has been a disincentive, especially for short-life, remote mines. However, there has been progress in making RE systems portable. In some instances, RE may be a suitable post-mining land use. This paper reviews 51 published examples of RE systems for mines. Nearly 86% of installed capacity is solar PV with the remainder being wind power. Most RE-powered mine sites are in Australia and Chile, but more countries are installing capacity. Most RE systems are at gold mines, followed by copper and iron ore. As RE is becoming more efficient and power requirements in mines are increasing as grades drop, it is likely that it will become a key part of energy supplied to the sector.

Introduction

Renewable energy

Renewable energy (RE), derived from replenishable planetary resources, is distinct from traditional industrial energy sources such as coal and uranium that are extracted from finite reserves. RE includes hydro, solar, wind, tidal, wave, biomass and geothermal energy sources.[1] Some[2] also view hydrogen as a source of RE, although it may more usefully be considered a way of transferring electrical energy to certain 'hard-to-decarbonise' applications,[3] and its 'green' credentials rely on the use of other forms of RE to produce the hydrogen in the first place.

Numerous arguments have been presented for an economy-wide transition away from fossil fuels to RE. Most of these pivot on the risks posed by carbon emissions to the global

1 Thomas Hillig, *A Hybrid Solution with Concentrated Solar Power (CSP) and Fuel for Baseload Mining Operations*, Ripasso Energy/THEnergy Study (Munich: THEnergy Sustainable Consulting, February 2016), 13.
2 Anglo American, "4 Ways the mining Industry Uses Renewable Energy", September 24, 2019.
3 International Renewable Energy Agency, *Hydrogen: A Renewable Energy Perspective* (Abu Dhabi: IRENA, 2019), 52.

climatic system. Yet, while RE production is rapidly expanding across a variety of industries, there is a widespread belief that current RE technologies are impractical for the mining and minerals sector.[4]

This paper gives an overview of recent trends in the application of RE in the mining sector. There are three general cases: use of RE to power exploration or production sites (mines/ plants); use of RE for community development projects; and RE as a post-mining land use. These can overlap – abandoned mining land can be used to supply energy to a new mine, a mini-grid on a mine can be turned over to the community post-mining, etc.

The extractives sector and energy use

Growing populations and increasing affluence have resulted in greater demand for minerals and metals. Mines have historically relied on commodity prices moving synchronously with energy prices and have consequently paid insufficient attention to minimising energy costs.[5] This is no longer the case: between 1973 and 2013 metal prices dropped by 7%, raw materials by 59% and food by 58%. Over the same period, energy prices increased by over 160%.[6]

Ore grades are generally falling, resulting in lower margins.[7] It is likely that lower ore grades and harder rocks will need to be processed in the future. Higher mass flow rates of ore will be required to deliver the same volume of metal and will need more energy for milling.[8] Where fresh water is limited, more energy will be required to power desalination.

Globally, the mining industry is already a significant energy consumer, using some 400 Terawatt-hours (TWh) of electricity annually.[9] In 2010 the sector accounted for 15% of total electricity usage, 11% of total final energy consumption and 38% of industrial final energy consumption.[10] The sector's energy demand appeared to be keeping pace with the broader global economy until recently: a 2018 report pegged the mining industry at 11% of global energy consumption,[11] but Mining Review[12] now has it at 6.2%.

In sub-Saharan Africa power demand by mining companies was expected to reach 23 443 megawatt (MW) in 2020, having increased nearly three-fold from 7 995MW in 2000.[13] Grid

4 B Fleet et al., "Prospects for Renewable Energy Systems in the Mining Industry", *CIM Journal* 6, no. 1 (2015): 27–34.
5 Fleet et al., "Prospects for Renewable Energy".
6 International Monetary Fund, World Economic Outlook: *Growth Resuming, Dangers Remain* (Washington DC: IMF, 2012), 299.
7 Fleet et al., "Prospects for Renewable Energy".
8 Jannik Haas et al., "Copper Mining: 100% Solar Electricity by 2030?", *Applied Energy* 262 (2020): 11.
9 Kateryna Zharan and Jan C Bongaerts, "Decision-Making on the Integration of Renewable Energy in the Mining Industry: A Case Studies Analysis, a Cost Analysis and a Swot Analysis", *Journal of Sustainable Mining* 16 (2017): 162–107.
10 International Energy Agency, *Energy Balances of Non-OECD Countries* (Paris: IEA, 2010), reported in BC McLellan et al., "Renewable Energy in the Minerals Industry: a Review of Global Potential", *Journal of Cleaner Production* 32 (September 2012), 32–44.
11 Fitch Solutions, 'Shift to Renewables to becoming a grwoing trend in mining', August 31, 2018.
12 John Lewis, "Mining Under Pressure to Transition to Renewable Energy", *Mining Review Africa*, March 2, 2020.
13 Sudeshna Ghosh Banerjee et al., *The Power of the Mine: A Transformative Opportunity for Sub-Saharan Africa*, Directions in Development Report (Washington DC: World Bank), 2015.

supply has been the dominant form of power consumed by mines in the region, but self-supply has risen rapidly from only 6% of projects prior to 2000 to 18% 20 years later.[14]

Bulk commodity and construction minerals are especially energy intensive and a significant source of greenhouse gases (GHGs). This profile has increased societal pressure on the sector. Mining companies are also under pressure from customers: for example, BMW has announced plans to reduce resource consumption per vehicle by 45% by the end of 2020.[15] BMW is a significant customer, having purchased 42 000 tonnes of copper in 2017.[16] The automaker's consumption is expected to increase to 62 000 tonnes by 2025.

Diesel

Fossil fuel-based electricity generation is commonly used on remote sites. Fossil fuels are also used extensively for mobile plants, typically in the form of diesel generators (gensets).[17] Gensets are better than solar photovoltaic (PV) systems when it comes to managing power factor variations, grid frequency and inertia, and short circuit currents. Gensets only convert 40% of the energy in fuel to electricity, with most of the remainder wasted as heat and noise.[18] Work on waste heat recovery to improve efficiencies has been shown to save 300 000 litres of diesel annually when used on two 1MW generators – no small ongoing saving given that diesel and oil costs doubled in the 10 years to 2013.[19] At the start of January 2013 oil was $93 a barrel, but declined to only $61 a barrel at the start of January 2020.[20] Use of gensets is likely to incur carbon taxes in those jurisdictions where these are not already levied. Additionally, the World Health Organization has declared diesel emissions carcinogenic.[21]

Under these circumstances, RE is a possible solution: a study of the GHG emissions from the Chilean copper mining industry showed that reductions of up to 60% could be achieved by replacing conventional energy sources with RE.[22]

RE in the mining sector

For the past decade, solar and wind have been seen as the principal sources of RE.[23] In the mining sector, Africa and Australasia are the continents where RE has had the most rapid

14 Banerjee et al., *The Power of the Mine*.

15 Thomas Hillig, Optimizing Costs of Renewable Energy for the Mining Industry, THEnergy/Voltalia Report (Munich: THEnergy Sustainable Consulting, February 2019), 14.

16 Fitch Solutions, "Shift to Renewables".

17 Fleet et al., "Prospects for Renewable Energy".

18 Thomas Hillig, System Optimization of Renewable Energy Microgrids with Heat Recovery in Remote Mining, THEnergy/Triogen Report, (Munich: THEnergy Sustainable Consulting, January 2020).

19 Michel Carreau, "Hybrid Power at Remote Mining Sites to Reduce Electricity Costs", *Journal of Canadian Institute of Mining, Metallurgy and Petroleum* (May 2013), 9.

20 MacroTrends, "WTI Crude Oil Prices: 10 Year Daily Chart".

21 World Health Organization and International Agency for Research on Cancer, "Diesel Engine Exhaust Carcinogenic", Press Release 213, June 12, 2012, 4.

22 Haas et al., "Copper Mining: 100% Solar".

23 C De Castro et al., "Global Solar Electric Potential: A Review of their Technical and Sustainable Limits", *Renewable and Sustainable Energy Reviews* 28 (2013): 824–835; Yosoon Choi and Jinyoung Song, "Review of Photovoltaic and Wind Power Systems Utilized in the Mining Industry", *Renewable and Sustainable Energy Reviews* 75 (2017): 1386–1391; Haas et al., "Copper Mining: 100% Solar".

roll-out at remote sites,[24] while Chile and Australia appear to have the highest number of mine site RE installations (see Figure 1). In the African setting, solar is commonly considered to be the best source. Of the two commonly employed solar technologies – concentrated solar power (CSP) and PV panels – PV is the most widespread.[25]

Africa currently harnesses about 8% of its hydropower potential.[26] Hydropower projects are typically complex, requiring extensive civil engineering works and more permits, and therefore longer planning horizons than either solar or wind projects. The author recently participated in a 5MW run-of-river mini-hydropower project that took more than two years to construct. However, the average lifespan of a hydro project, at 50–100 years, is considerably longer than that of solar or wind.[27]

The use of high-flow, low-head Kaplan turbines is increasing the rate of uptake of hydropower at mine sites in countries with favourable hydrology, such as the Democratic Republic of Congo. These turbines are similar in design to a ship's propeller and can operate at heads as low as 3m (ie, they operate at pressures equivalent to that arising from a 3m water column). To illustrate this, a Kaplan turbine can generate 9MW at a flow rate of 100m3/s but a head of only 10m, whereas a Francis turbine producing the same power would require only 10m3/s of flow but a head of 100m.[28]

No biomass energy technology could be identified in the literature as a primary supply to mines. In spite of East Africa's Rift Valley having a geothermal potential of 17GW,[29] and geothermal energy having superior base load characteristics relative to wind and solar, there are no reports of mining companies exploiting this energy source. This may be in part due to very high capital expenditure (capex) requirements and extended installation times. In granite areas, between 3 000 and 5 000m have to be drilled.[30] There is, however, payback for long-life operations: lifetime savings have been calculated to be three times that of a wind hybrid.[31]

Both hydropower and biomass technology are limited by the availability of suitable locations – appropriate catchments in the former and adequate growing conditions in the latter. Wind energy is also restricted to locations with constant, elevated wind speeds.[32] De Castro et al. suggest that solar is the most likely source of energy to supply the current global demand.

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24 Hillig, *System Optimization of Renewable Energy*.

25 Hillig, *A Hybrid Solution with Concentrated*.

26 Banerjee et al., *The Power of the Mine*.

27 Hillig, *Optimizing Costs of Renewable*.

28 David Still (Consulting Engineer), personal communication with Daniel Limpitlaw, April 2020.

29 Banerjee et al., *The Power of the Mine*.

30 Roman Guenter Votteler and Alan Colin Brent, "A Mining Perspective on the Potential of Renewable Electricity Sources for Operations in South Africa: Part 1. The Research Approach and Internal Evaluation Process", *Journal of the Southern African Institute of Mining and Metallurgy* 117, no. 3 (2017): 285–297.

31 Votteler and Brent, "A Mining Perspective … Part 1".

32 De Castro et al., "Global Solar Electric Potential".

Average global solar energy density[33] is 168 watts per square metre (W/m2). Conversion of this energy into electrical energy using PVs yields[34] between 12 and 25 electric averaged watts per square meter (We/m^2). Additionally, PV performance degrades in high irradiance areas like hot deserts (long evacuation lines, temperature and dust losses). De Castro et al.[35] argue that solar and wind will be the two principal sources of RE used to replace fossil fuels, but that the limits of these are below the current level of fossil fuel energy consumption. Consequently, a transition to lower per capita energy consumption is essential. McLellan et al.[36] reported that (at the time, assuming 10–15% panel efficiency and 3 megajoules per square metre [MJ/m^2] daily insolation), the industry would require between 5 and 15% of all mined land to be covered with panels to supply the entire sector.

While use of RE in the mining sector has been expected to reach 8% by 2022,[37] it must be stressed that on sites with RE installations it only accounts for 10–20% of their generated electricity owing to the intermittent nature of solar and wind.[38]

Energy and production costs

Energy's contribution to mining capital expenditure is reportedly 25%.[39] It is seldom less than 10% and frequently exceeds 25% of operating expenditure.[40] Some estimates have it between 20% and 30% of the total cost of production,[41] and Fitch[42] reported that energy accounts for up to 30% of mining company balance sheets.

This has not resulted in wholesale conversion to RE over the past decade. Falling oil prices have retarded the uptake of RE while not stopping it.[43] The recent Saudi–Russia price war and the impact of the COVID-19 pandemic, resulting in a collapse of the oil price from $51.50 on 31 January 2020 to a low of $21.26 on 21 April 2020,[44] will also harm the uptake rate. The effect this will have in the medium term remains to be seen (oil prices had recovered to around $60 per barrel by March 2021 but were not expected to increase further in the medium term).

33 Weston A Hermann, "Quantifying Global Exergy Resources", *Energy* 31 (2006): 1349–66.

34 De Castro et al., "Global Solar Electric Potential".

35 De Castro et al., "Global Solar Electric Potential".

36 McLellan et al., "Renewable Energy in the Minerals".

37 R Martin, "Renewable Energy Will Supply At Least 5 Percent of Power Demand for the Mining Industry by 2022", Navigant Research, Press Release, 2014, quoted in Zharan and Bongaerts, "Decision-Making on the Integration".

38 Hillig, *System Optimization of Renewable Energy*.

39 Carreau, "Hybrid Power at Remote".

40 Banerjee et al., *The Power of the Mine*.

41 RL Miller, "Energy Analysis Is a Key for Miner Profitability" (Proceedings, SME Annual Meeting, Preprint 17-056, Denver, February 19–22, 2017), 4.

42 Fitch Solutions, "Shift to Renewables".

43 Thomas Hillig, *Low-load Gensets for Solar-Diesel Hybrid Plants in the Mining Industry*, THEnergy Study (Munich: THEnergy Sustainable Consulting, October 2015), 13.

44 MacroTrends, "WTI Crude Oil Prices".

As if to outdo the oil price drop, PV costs are down more than 90% since the 1970s and are expected to decline by 20% for each doubling of capacity (recently every three years).[45] PV prices are still dropping: in 2020 single-axis tracking PV systems had an expected life of 30 years and capex of around $813,000/MW installed capacity with operating costs of $12,000/MW. Over the next 30 years, capex is expected to drop to $360,000/MW and operating costs to $5,400/MW. At that point, the operating life of a PV system is expected to have increased to 40 years.[46]

While overall costs of RE have come down substantially since 2005, and PV systems dropped by 75% over the 10 years to 2016,[47] RE still has a high initial capex and requires 10–20 years before a lower total cost of ownership is achieved relative to traditional power sources.[48] The move to RE entails a shift from low capex/high operating expenditure (opex) to high capex/low opex. This may deter junior mining companies from adopting RE for projects, as they are often more sensitive to capital raising during construction than to higher opex once the mine is built. However, for remote mines on diesel generators the relatively lower RE operating cost insulates the mine from future fuel price increases.

Nearly a decade ago, capex for a remote mine site RE project could be expected to cost $10–50 million ($2.5–4 million per installed MW) and the return on investment was typically seven years. In 2013 the cost of wind/solar was 15–22 cents/kWh (assuming good wind/sun resources). This represented an energy cost saving of 10–20% with price certainty for 20–25 years.[49] If present-day grid power costs remain constant, it will be cheaper to run a mine fully off solar RE by 2050.[50]

Challenges

Supply versus demand on mine sites

The power demand quantum of a mine varies with size, commodity (precious metals/bulk commodity/base metals), location and stage in life cycle.[51] Notwithstanding this inter-mine variability, the power demand on any particular mine site is relatively constant, as mines commonly require a 24-hour supply of uninterrupted, baseload electricity.

Underground mines reportedly consume more electricity than surface mines owing to hauling requirements, ventilation and water pumping – in the US, surface coal operations

45 Fleet et al., “Prospects for Renewable Energy”.

46 Haas et al., “Copper Mining: 100% Solar”.

47 Thomas Hillig, *Mobile Solar- and Wind Diesel Hybrid Solutions for Mineral Exploration*, Pfisterer/THEnergy Study (Munich: THEnergy Sustainable Consulting, October 2016), 14; Zharan and Bongaerts, “Decision-Making on the Integration”.

48 Fleet et al., “Prospects for Renewable Energy”.

49 Carreau, “Hybrid Power at Remote”.

50 Haas et al., “Copper Mining: 100% Solar”.

51 Fleet et al., “Prospects for Renewable Energy”.

consume 30–40% less electricity than underground collieries.[52] A typical North American underground mine consumes approximately 100kWh/tonne of ore production, with up to half of this being for heating, ventilation and air conditioning purposes.[53]

Solar and wind, the two most widely used RE sources, are both influenced by location, temperature, altitude, season and time of day.[54] They are thus subject to intermittent production (steep supply curves) and, consequently, stand-alone solar or wind systems are unsuitable for powering mines.[55] One way of flattening the RE supply curve is to include energy storage systems such as batteries – without storage, solar reportedly only meets an average of 30% of a constant demand.[56]

Another approach is to reduce energy consumption and ensure that most energy is consumed when RE resources are available.[57] For example, scheduling higher power demand during daylight (especially middle portions of the day) allows for higher PV penetration without significant storage costs.[58] An example from the copper industry involves a proposal to preferentially grind harder ore materials during daylight hours when solar resources can supply the additional power required.[59] Other examples include electrification of the hauling fleet, use of stockpiles to increase processing flexibility and limiting high energy demand activities to daylight hours (for solar RE systems).

If rescheduling energy demand is impractical, the three options for employing RE at mines are: RE with storage; hybrid stand-alone; or hybrid with storage.[60] Typically, RE reduces diesel consumption by 10–20% in a hybrid configuration with diesel generators. Owing to the need for backup, this does not reduce the number of generators required (unless energy storage is also used).[61]

Votteler & Brent[62] recommend that all RE should go into the primary load and at peak output, and that supply should not exceed the mine's demand. Consequently, a grid-tied system with limited RE generation is usually most efficient for decreasing costs and GHG emissions, and providing a degree of energy independence. However, This approach may

52 Perrine Toledano, "Leveraging the Mining Industry's energy Demand to Improve Host Countries' Power Structure" (Policy Paper, Columbia Centre on Sustainable Investment, New York, 2012), 41.

53 Seyed Ali Ghoreishi-Madiseh et al., "Ice Versus Battery Storage: A Case for Integration of Renewable Energy in Refrigeration Systems of Remote Sites", *Energy Procedia* 159 (2019): 60–65.

54 Fleet et al., "Prospects for Renewable Energy".

55 Roman Guenter Votteler and Alan Colin Brent, "A Literature Review on the Potential of Renewable Electricity Sources for Mining Operations in South Africa", *Journal of Energy in Southern Africa* 27, no. 2, (2016): 21.

56 Shahriyar Nasirova and Claudio A Agostini, "Mining Experts' Perspectives on the Determinants of Solar Technologies Adoption in the Chilean Mining Industry", *Renewable and Sustainable Energy Reviews* 95 (2018): 194–202.

57 Carreau, "Hybrid Power at Remote"; Fleet et al., "Prospects for Renewable Energy".

58 C Chambers, "Off-Grid Solar in the Mining Sector: Can Renewable Energy Reduce your Operating Costs?" (Proceedings, Metallurgical Plant Design and Operating Strategies, Perth, July 15–17, 2013), 15.

59 Haas et al., "Copper Mining: 100% Solar".

60 Votteler and Brent, "A Literature Review".

61 Hillig, *System Optimization of Renewable Energy*.

62 Votteler and Brent, "A Literature Review".

lack flexibility, as scaling up grid-tied RE systems is difficult: few mining jurisdictions have a regulatory framework that enables companies to sell excess power back into the grid.[63]

RE project risks

Perception

As recently as 2013 many mining companies still viewed RE as 'unproven technology'.[64] Companies with little experience of RE saw it as increasing investment risk – it was not commonly core business.[65] In many mining areas RE service infrastructure is not fully developed[66] and the technology is regarded as complicated, with installation at remote sites compromised by skills shortages.

Technology

Votteler and Brent[67] identified overall system efficiency of RE as the principal technical risk for mining projects. They also identified capacity factor, system reliability and technology maturity as risks. Chambers[68] reported that PV panels are less efficient at higher temperatures and in dusty areas, and therefore regular panel washing is required to avoid reduced generation. These are drawbacks for use of PV systems in hot, dry places. Some advances have been made: frameless panels are less affected by dust and the angle of panels can be adjusted to reduce dust accumulation. Hydrophobic nano-coatings have also been developed to retard build-up on panel surfaces.[69]

Social acceptance

From an economic perspective, Votteler and Brent[70] reported that the investment costs threatened project viability, and social acceptability and job creation were headline issues socio-politically. In remote mining sites, especially in Africa, jobs are scarce and in great demand by local communities. RE construction projects offer few jobs, and most of these are highly skilled. This mismatch is especially of concern during mine construction, when demand peaks for highly skilled workers.[71] It is less acute during operations, as routine maintenance can be undertaken with limited staff numbers and with skills supplemented by remote monitoring. This does not help with job creation, though, potentially increasing local hostility to RE. Wind is reported to have a slightly lower job creation potential and slightly longer implementation period relative to solar for hybrid installations with similar performance characteristics.[72]

63 Nasirova and Agostini, "Mining Experts' Perspectives".
64 Fleet et al., "Prospects for Renewable Energy".
65 Carreau, "Hybrid Power at Remote".
66 Votteler and Brent, "A Mining Perspective ... Part 1".
67 Votteler and Brent, "A Mining Perspective ... Part 1".
68 Chambers, "Off-Grid Solar".
69 Chambers, "Off-Grid Solar".
70 Votteler and Brent, "A Mining Perspective ... Part 1".
71 Chambers, "Off-Grid Solar".
72 Votteler and Brent, "A Mining Perspective ... Part 1".

In spite of these misgivings, RE includes several well-proven technologies. While large, off-grid RE mine supply projects are a relatively recent phenomenon, Australia has had solar hybrid power supply to remote towns for a decade or more.[73] In 2019 the International Renewable Energy Agency reported that nearly 623GW of wind, 580GW PV and 6GW of CSP capacity had been cumulatively installed globally (across all sectors, not only mining).[74]

Heating energy demand

Not all energy demand in the minerals sector is electric – energy is also required for heating. Electricity consumption only accounts for 20% of energy use and 33% of total industry emissions in the mining sector.[75] Despite this, electricity generation has been the key focus of RE technology and therefore the requirement for high-temperature thermal processes is a major challenge for decarbonising mineral processing.[76] In the Chilean copper industry, for example, direct consumption of fossil fuels (Scope 1) is equivalent to electricity purchases (Scope 2). Some of the Scope 1 emissions are related to use of generators on remote sites, but much of it will be process or transport related. Transitioning to hybrid or electric vehicles (EVs) will go some way to assist with the conversion to RE.[77] Transport emissions are very important in some sectors: processing iron ore in its country of origin to avoid bulk ore transport could save 6–8% of iron and steel emissions.[78] This does not solve the heating energy conundrum, however.

Chandia et al.[79] report that use of flat plat collectors[80] (FPCs) to heat water at a Chilean copper mine could dramatically reduce energy costs and GHG emissions. As they have a low to medium temperature requirement, copper beneficiation processes best suited to integration with solar heating are electrowinning and electrorefining. In their case study, Chandia et al. found that use of FPCs with an area of 31 000m^2, at a mine producing 160 kilotonnes per annum (kt/a) of copper, resulted in a long-term cost 80% lower than that of conventional diesel boilers. The FPCs were used in conjunction with diesel boilers to enable 24-hour operations. By using the FPCs, more than 14kt of CO_2 emissions are avoided annually. These authors also report that use of solar thermal energy in copper heap leaching could increase recovery by up to 5%.

If solar were to be rolled out to all mines/plants with good solar resources, McLellan et al.[81] calculated that only 9% of the industry's thermal energy usage would be supplied (if blast

73 Chambers, "Off-Grid Solar".

74 International Renewable Energy Agency, *Renewable Capacity Statistics 2020* (Abu Dhabi: IRENA, 2020), 66.

75 McLellan et al., "Renewable Energy in the Minerals".

76 McLellan et al., "Renewable Energy in the Minerals".

77 Haas et al., "Copper Mining: 100% Solar".

78 McLellan et al., "Renewable Energy in the Minerals".

79 Eduardo Chandia et al., "Analysis of the Energy Demand of the Chilean Mining Industry and its Coverage with Solar Thermal Technologies", *Int. J. Sustain. Eng 9*, no. 4 (2016): 240–250.

80 A flat plate collector consists of a sheet of copper or aluminium, painted black to maximise heat absorption and overlain with parallel copper tubes. Incoming solar radiation heats the plate, transferring heat to the fluid in the tubes (commonly water). The plate and tubes is enclosed in a metal housing with glass or plastic sheeting covering it to create an insulting air space.

81 McLellan et al., "Renewable Energy in the Minerals".

furnace and coke ovens were included). This could be further reduced by energy storage limitations for high-temperature applications – they could either shut down at night or use fossil fuels for combustion, thus reducing solar to 3% of the sector's thermal energy requirement. While solar has potential for mine-site applications, it is unlikely to supply all of the energy required for thermal mineral processing in the near future.

The case for RE

Hybrid systems

Low RE penetration in a hybrid system means that traditional power sources, such as diesel generators or the grid, are expected to run much of the time and carry the load. High RE penetration means that RE carries most or all of the load at certain times, with traditional power sources acting as a top-up. In low penetration scenarios, the variability of RE is not a challenge[82] as the spinning reserves[83] of the generators absorb the power variations. Energy generation must equal the system load at all times. Diesel generators typically operate at 85% of capacity (larger ones at not less than 75%).

Because solar PV is subject to interference by cloud cover and wind is often changeable, power generation can be intermittent. At low penetration levels, the system can accommodate solar ramping,[84] but at higher levels, flywheels or batteries are required to keep the system stable.

Hybrid energy systems have facilitated greater RE penetration.[85] Several hybrid combinations are available for mines,[86] including:

- diesel generators and solar PV;
- diesel generators and wind power;
- diesel generators and geothermal power;
- grid connection and solar PV;

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82 Carreau, "Hybrid Power at Remote".

83 The unused capacity in a generator available for supplying power during a shortage is termed the "spinning reserve". To supply this emergency power, a diesel generator is typically run below its rated power output so that it can quickly ramp up output if required – see David Wenzhong Gao, *Energy Storage for Sustainable Microgrid* (Amsterdam: Elsevier, 2015), 35–77. Two 10MW generators with an 18MW load have a spinning reserve of 2MW.

84 This refers to the rate of change in energy generation – as a cloud passes over a PV system, the power drops away, returning once it is exposed to sunlight again. For a constant demand, power from other sources (like batteries) needs to be supplied rapidly during the reduction of in power from the PVs.

85 Jun Chen and Christian Rabiti, "Synthetic Wind Speed Scenarios Generation for Probabilistic Analysis of Hybrid Energy Systems", *Energy* 120 (2017): 507–517.

86 Votteler and Brent, "A Literature Review".

- grid connection and wind power; and
- grid connection and geothermal power.

A microgrid control system is able to smooth out interruptions in RE power by synchronising the fluctuating output from solar/wind generators with the loads on the mine and drawing on energy from conventional components of hybrid systems.[87]

Wind and solar hybrid systems

As shown previously, solar, wind and hybrid power are the preferred RE systems on mine sites. By 2016, 91% of RE installations at mines were either solar or wind.[88] There are a number of factors influencing the selection of an RE system, but hybrid wind power is often favoured in higher latitudes and hybrid solar power elsewhere. Both of these can be grid-tied or stand-alone.

It has been reported that a majority of areas with significant mining activity have annual radiation exceeding[89] 2 000kW/m². Most installed solar generating capacity on mine sites is provided by PV. In arid zones single-axis tracking PV systems are the most commonly used technology.[90] In 2016 only one mining CSP project could be identified: supplying a grid-connected operation in Chile.[91]

Votteler and Brent[92] reported that solar had the highest potential for use at mines in South Africa at the time of their review. While capex was approximately three times that of traditional power sources, it was low relative to other RE systems. Levelized costs were half those of diesel and approximately the same as grid power.

The high cost of connecting to the grid in mining jurisdictions, where it may cost several million dollars even for locations that are not remote from the grid,[93] makes RE attractive. Grid supply costs may also be prohibitive: in South Africa, the cost of grid supply increased by 346% between 2007 and 2015 (see Figure 1). It is interesting to note that, globally, the largest grid-connected RE projects have generally been larger than the largest off-grid installations (largest reported 6.7MW vs 115MW).[94]

Without energy storage, 25% of energy required by a mine in a high solar irradiance region can be replaced by solar. In areas of good quality wind resources, up to 30% of the mine's

87 Hillig, *Optimizing Costs of Renewable*; Fleet et al., "Prospects for Renewable Energy".
88 Votteler and Brent, "A Literature Review".
89 Votteler and Brent, "A Literature Review".
90 Haas et al., "Copper Mining: 100% Solar".
91 Votteler and Brent, "A Literature Review".
92 Votteler and Brent, "A Literature Review".
93 Thomas Hillig, *Renewable Energy as a Leverage for Mining Companies in Negotiations with Utilities and Diesel Suppliers*, THEnergy Study (Munich: THEnergy Sustainable Consulting, 2015), 11.
94 Votteler and Brent, "A Literature Review".

The high cost of connecting to the grid in mining jurisdictions, where it may cost several million dollars even for locations that are not remote from the grid, makes RE attractive

energy can be supplied by wind turbines.[95] In an assessment of RE in the South African mining sector, Votteler and Brent[96] found that a wind hybrid system saved around $4 million over the life of the project considered, compared to $3.3 million for a solar hybrid relative to the diesel base case. In South Africa, wind has lower availability than solar.[97]

Diesel is the dominant power source

Diesel currently dominates power supply at remote mining and exploration sites, but is expensive and likely to become even more so. Diesel power is prevalent in many developing country settings owing to the unavailability or unreliability of grid power. Electricity outages can result in millions of dollars lost on a daily basis. There are also time delays in restarting and ramping back up, as well as safety implications when supply is lost[98] – hoisting in vertical shafts and reticulating ventilated air in deep mines are obvious examples. In remote settings, the logistics of diesel supply can be daunting, resulting in outages and degrading the economic case for diesel – a reliable fuel supply is key to energy generation economics.[99]

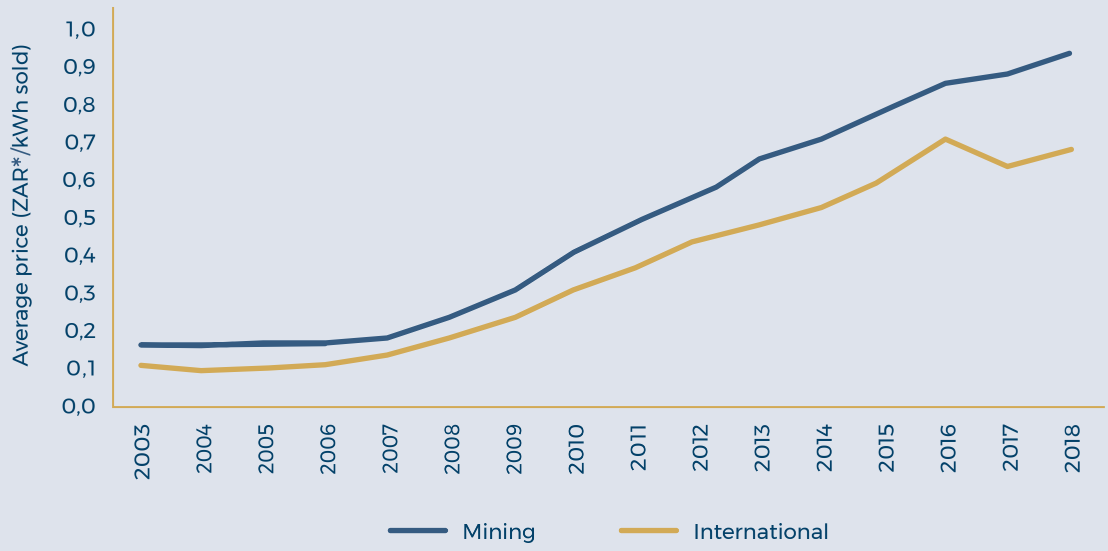
Diesel currently dominates power supply at remote mining and exploration sites, but is expensive and likely to become even more so

Generally, fossil fuel prices and grid electricity prices are expected to rise over time. The latter is especially true in Southern Africa, where grid electricity rates increased five-fold between 2003 and 2018 (see Figure 1). Early adopters of RE were largely motivated by carbon reduction and long-term ecological sustainability considerations. More recently,

95 Thomas Hillig, *The Influence of Renewable Energy on the Market Value of Mining Companies*, THEnergy Study (Munich: THEnergy Sustainable Consulting, November 2014), 10.
96 Votteler and Brent, "A Mining Perspective … Part 1".
97 Votteler and Brent, "A Literature Review".
98 Chambers, "Off-Grid Solar".
99 Miller, "Energy Analysis Is a Key".

RE is being adopted to ensure energy independence and stable supply while reducing operating costs.[100]

Figure 1 Historical price increases in grid power to mines in South Africa and neighbouring countries



* ZAR = currency code for South African rand

Source: Eskom, "*Tariff History*"

Solar PV can be used as a hedge to manage the price risk, as the bulk of PV-related costs are incurred during construction. Overall costs decrease over the lifetime of the system since there are no fuel costs and very low maintenance costs.[101] Diesel generators require little initial investment and limited space, and are quickly installed, but operating costs are high and unpredictable owing to fluctuations in fuel prices.[102] Integrating diesel generators with PV in a hybrid system increases the initial capital investment, but significantly reduces costs over a 20-year period. This also reduces GHG emissions. A capital-efficient approach may be to start operating with diesel generators and then to replace them with hybrid PV as soon as the mine's dept burden has been reduced.

While wind or solar systems may reduce electricity costs, higher RE penetration may lessen overall efficiency as diesel generators should be run under high loading.[103] Low

100 Fleet et al., "Prospects for Renewable Energy".

101 Thomas Hillig, *Solar Projects, Energy Efficiency and Load Shifting for an Optimized Energy Management in the Mining Industry*, Cronimet/THEnergy Study (Munich: THEnergy Sustainable Consulting, September 2015), 16.

102 Votteler and Brent, "A Mining Perspective … Part 1".

103 Jakob Janzen et al., "Battery Energy Storage as a Way to Reduce Remote Mine Electricity Costs" (Proceedings, World Mining Congress, Montreal, 2013), 11.

loads damage the generators and are inefficient. This means either that PV penetration must be kept low to account for the ramping that occurs as clouds pass overhead, or that substantial storage is required to supply the system when the PV drops off. In the past, additional spinning reserve to stabilise RE hybrid systems has been provided by diesel generators. These are typically slow to start up, cannot be run under low loads and are not sufficiently flexible to balance the unstable solar or wind component of the system. Hillig[104] reports that generators can be modified to permit running under low-load conditions while consuming limited quantities of diesel. With such modifications, they can react quickly to changes in output from the RE source or changes in demand. These new generators will enable hybrid RE systems to operate at higher levels of efficiency while maximising RE penetration. The typical payback period of 15–20 years for a mine PV-hybrid system can reportedly be reduced to four to seven years using low-load generators.

The feasibility of using PV-diesel hybrid mini-grids to power mines has been proven for large- and small-scale applications.[105] However, solar PV hybrid systems should be used to offset diesel usage rather than replace capacity in the system if reliability is to be maintained.[106] With this approach, remote sites with high diesel costs should be able to achieve fuel savings of 40% with solar. In good wind areas, savings may be higher, but most sites are not suitable for wind.[107]

Energy storage

As is evident from the preceding discussion, matching the intermittent generating capacity of RE with the relatively constant demand at mines is challenging. Energy storage is key to achieving this without generators providing large spinning reserves. In some instances, savings may not come from reductions in diesel consumption but from increased operational efficiencies in the existing system through spinning reserves created by storage systems.[108] Spinning reserves may also need to accommodate reduced energy demand. Use of energy storage allows diesel generators to run at higher power and with higher efficiency, as it provides the spinning reserve.[109] The use of large storage capacity also enables higher RE penetration.

Matching the intermittent generating capacity of RE with the relatively constant demand at mines is challenging

104 Hillig, *Low-load Gensets*.

105 Deutsche Gesellschaft für Internationale Zusammenarbeit, *Subsector Analysis: Zambia – The Power Crisis and Its Consequences for Solar Energy in the Zambian Mining Sector* (Berlin: GIZ, 2016).

106 Chambers, "Off-Grid Solar".

107 Hillig, *The Influence of Renewable*.

108 Janzen et al., "Battery Energy Storage".

109 Janzen et al. "Battery Energy Storage".

Energy storage options include compressed gas, water, batteries and flywheels.[110] Battery energy storage systems (BESS) are the most widely used. Hydrogen storage systems are a high capex alternative to BESS. BESS consists of batteries (determining energy capacity) and inverters/chargers (determine the power capacity). Hydrogen storage systems consist of an electrolyser (to convert power to hydrogen gas [H_2]), a methaniser (to generate methane [CH_4] from carbon dioxide [CO_2] and H_2), a gas tank to store methane and a gas turbine (to convert methane to power). The turbine has a scrubber to recover CO_2 for use in methanisation.[111]

Energy storage has historically been a significant capital outlay. Costs are expected to fall, however. Haas et al.[112] predict that BESS capex will drop from around $109/kW in 2020 to $28/kW in 2050, while hydrogen storage systems system capex will drop from $2,442/kW to $1,232/kW in 2050.

Technology lifespan

Wind and solar have historically been intended for permanent installation. This can be problematic in isolated locations when their lifespan exceeds that of the mine they supply. This difficulty is enhanced in the case of exploration activities, where a camp typically remains in place for one to eight years (seldom longer) while RE installations typically have a lifespan exceeding 20 years.[113] Power demand at an exploration camp can be significant: diesel generators for exploration sites may be 10–150 (kilovolt-amperes [kVA])[114] or greater. In the author's experience, an exploration camp in the Congo used two 250kVA generators when the drilling programme was underway and there were 140 residents in camp, and two 80kVA generators under standby conditions. PV is modular, so a camp or mine could start with a small installation (low penetration) and increase size as batteries become economically viable[115] or as production commences. This approach is facilitated by the short construction times for PV systems.[116]

Due to optimised mounting systems, containerisation and high-efficiency PV panels, modern RE systems can now be made portable and moved, even at exploration sites.[117] Portable PV systems can be moved to another site at the end of the mine's life.[118] This is an important breakthrough, as the high initial capex generally makes RE only affordable over

110 Carreau, "Hybrid Power at Remote".
111 Haas et al., "Copper Mining: 100% Solar".
112 Haas et al., "Copper Mining: 100% Solar".
113 Fleet et al., "Prospects for Renewable Energy".
114 Hillig, *Mobile Solar- and Wind Diesel*.
115 Chambers, "Off-Grid Solar".
116 GIZ, "Subsector Analysis: Zambia", 13.
117 Thomas Hillig, *Modular, Semi-Portable Mounting Systems for Solar in the Mining Sector*, Nuance Energy/THEnergy Study (Munich: THEnergy Sustainable Consulting, May 2018), 12.
118 Chambers, "Off-Grid Solar".

longer time periods. In their analysis of the South African case, Votteler and Brent[119] found that, over five years, grid supply was the cheapest source of power, over 10 years hybrid PV was cheaper than the grid, and over 20 years wind and PV hybrids beat the grid.

For PV, the panel mounting system is key to determining the ease of removal or rehabilitation of a solar farm.[120] Previously, concrete foundations were poured. If earth anchors are used, four people can erect a 128-panel solar array in eight hours with no heavy equipment required. In instances where the container is part of the PV foundation, costs of moving containerised PV are in the range of 5–10% of the initial capex.[121]

Post-mining land use

Thousands of hectares of rehabilitated, marginal land have potential for RE – solar, wind or biofuel.[122] Such areas often have poor soil conditions (low organics, high compaction) and are not suitable for agriculture. Technology advances in wind turbines (higher hub heights, larger rotor diameters, higher efficiency turbines) allow wind farms to be installed in areas with lower-class wind resources,[123] making more former mine land available to this use.

The use of deep-level gold mines in South Africa for pump storage is another example of post-mining RE land use. For this, water flows from reservoirs in upper levels of the mine to a reservoir at lower levels via a pipeline system in the shaft that is connected to turbines during peak times. During off-peak times, the water is pumped back up to the upper reservoir. Income is generated through the differential costs between peak and off-peak periods. A further advantage of this system is that it can deal with ingress of water by allowing controlled surface discharges, and it pays for pumping costs.[124]

There are a number of examples of use of post-mining land for RE generation (see Figure 2). Generally, the scale of these installations is greater than that found at operating mine sites – these are more like utility installations.

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119 Roman Guenter Votteler and Alan Colin Brent, "A Mining Perspective on the Potential of Renewable Electricity Sources for Operations in South Africa: Part 2. A Multi-Criteria Decision Assessment", *Journal of the Southern African Institute of Mining and Metallurgy* 117, no. 3 (2017): 299–312.

120 Hillig, Modular, *Semi-Portable Mounting*.

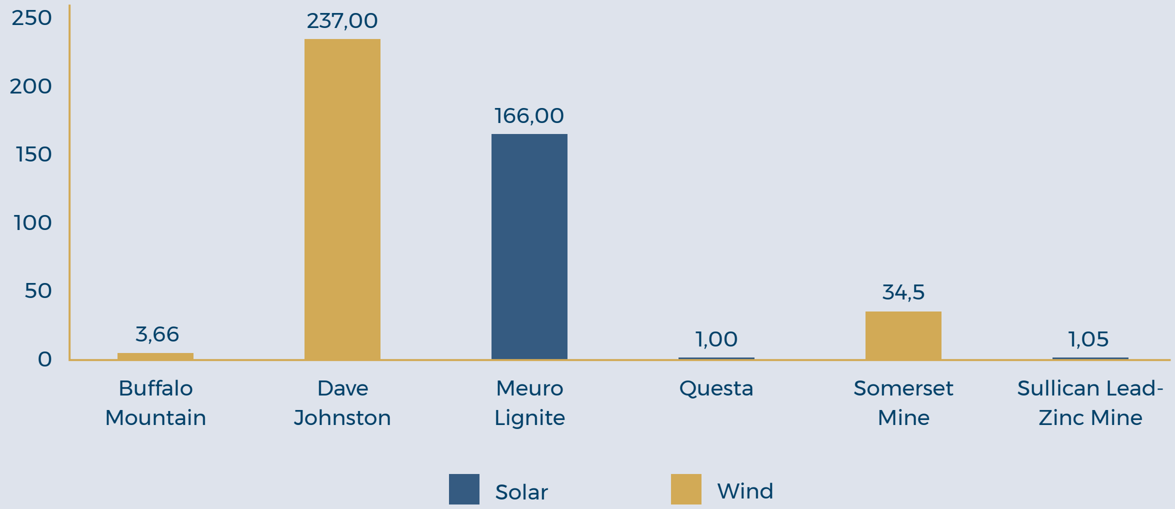
121 Thomas Hillig, *Solar-Diesel-Hybrid Power Plants at Mines: Opportunities for External Investors*, THEnergy Study (Munich: THEnergy Sustainable Consulting, December 2014), 11.

122 George Carico, James Wolfe and Tony Szwilski, "Renewable Energy and Property Re-Use on Surface Mined Lands", *Journal of the Canadian Institute of Mining, Metallurgy and Petroleum* (August 2013): 6.

123 Carico, Wolfe and Szwilski, "Renewable Energy and Property".

124 Frank Winde, Friederike Kaiser and Ewald Erasmus, "Exploring the Use of Deep Level Gold Mines in South Africa for Underground Pumped Hydroelectric Energy Storage Schemes", *Renewable and Sustainable Energy Reviews* 78 (2017): 668–682.

Figure 2 Installed capacity at abandoned mine sites



Source: Yosoon Choi and Jinyoung Song, "Review of Photovoltaic and Wind Power Systems Utilized in the Mining Industry", *Renewable and Sustainable Energy Reviews* 75 (2017)

Examples of RE in mines

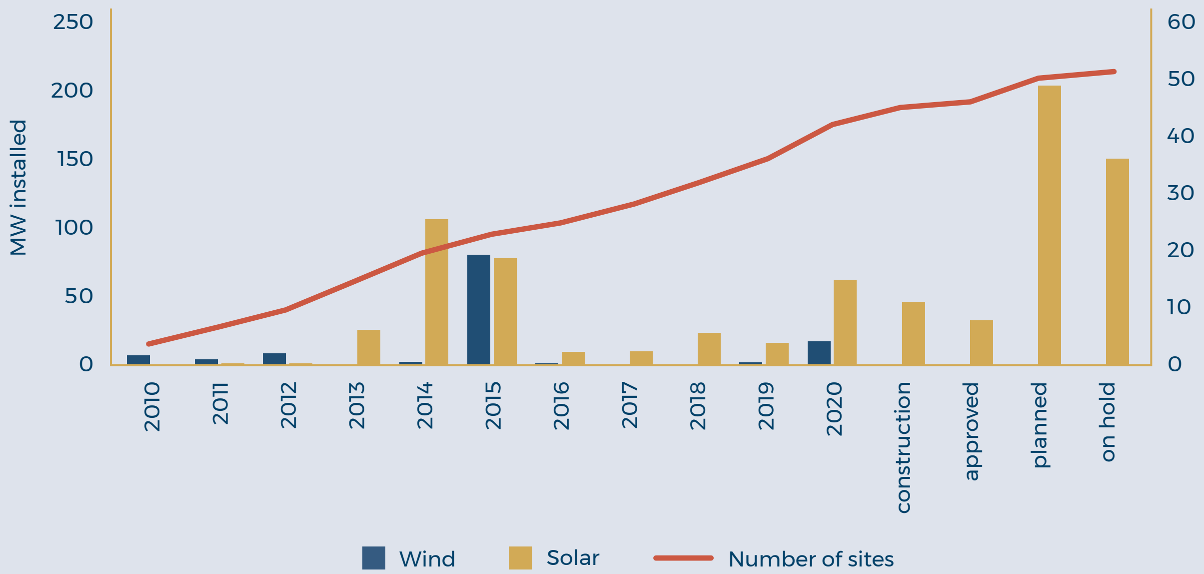
Over the last decade there has been a steady uptake of both wind and PV RE at mine sites. In 2017 Fitch Solutions reported that 1GW of RE-generating capacity had been installed at mine sites globally, with wind power leading (59%), followed by PV (37%) and solar thermal (4%).[125] Details of 51 mine-related RE projects could be found in the literature (see Figure 3). This excludes large utility-scale projects that happen to supply mines. At these 51 project sites, wind power (12 sites) accounts for an installed capacity of 128MW (around 14%) and solar PV (44 sites) for 777MW (nearly 86%). Five mines have both wind and PV installations (although not always adjacent to each other – one company has PV on the mine site and wind at the port). No case studies for hydropower or biofuel could be located. A total of 13 of the sites provided details on the installed diesel capacity, with the RE component representing as little as 1% to well over 90% of the installed diesel capacity. The average is around 40%.

Over the last decade there has been a steady uptake of both wind and PV RE at mine sites

125 Fitch Solutions, "Shift to Renewables".

In December 2019 the Energy and Mines World Congress claimed that 2019 would be seen as the tipping point for the adoption of solar and wind power in the mining sector.[126] This was based on the number of new projects announced. Considering the actual number of projects commissioned, as shown in Figure 3, that tipping point may not yet have been reached.

Figure 3 Installed capacity of RE at mine sites and mine-dedicated power parks



Source: Compiled by author

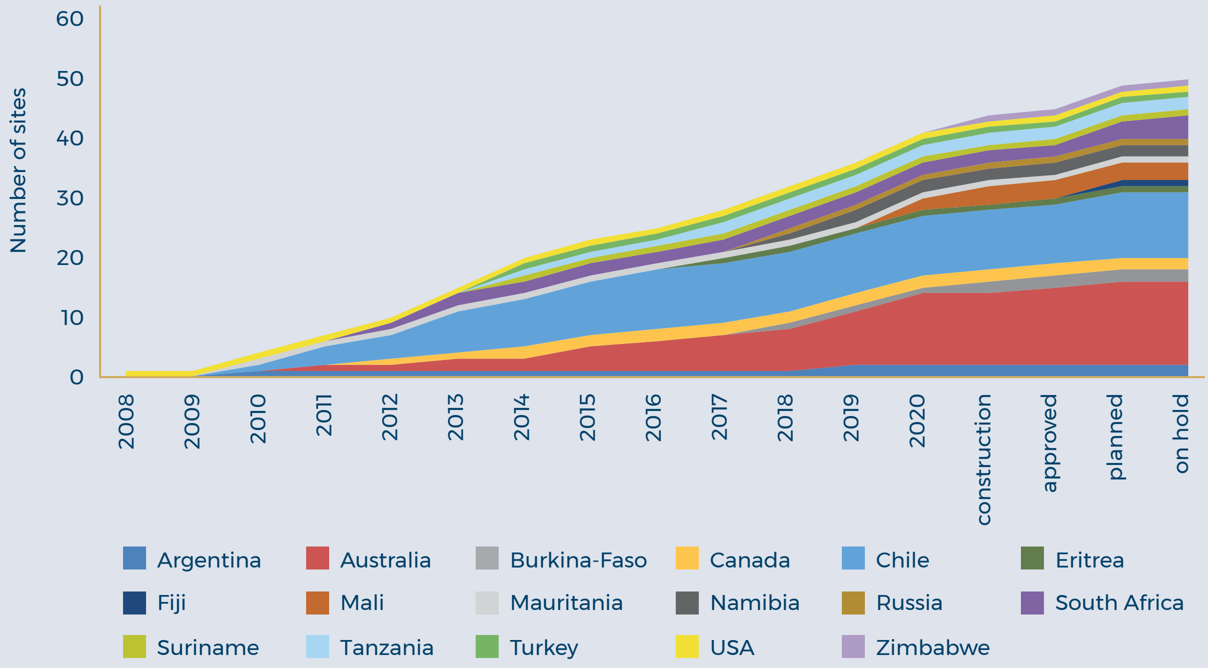
The economic argument for installing RE is becoming increasingly compelling, but environmental considerations also appear to be a significant factor. Of the 51 projects shown in Figure 3, 14 report on reductions in carbon emissions, totalling in excess of 1 million tonnes annually. There are some examples of innovative use of RE. Anglo American, for example, has constructed a pilot project at its Los Broncas copper mine in Chile that consists of 256 PV panels installed over the tailings storage facility pond. This has reportedly not only reduced evaporative losses by 80% but generates 86kW of power, thus saving water and generating power.[127]

Australia and Chile dominate the geographic spread of installed mine RE systems: Australia has 14 and Chile 12. In 15 other countries RE has been installed at mine sites since 2008, the first reported instance being at Barrick's Goldstrike mine in the US (see Figure 4).

126 ThEnergy, "Renewable Energy and Mining".

127 Anglo American, "4 Ways the Mining Industry".

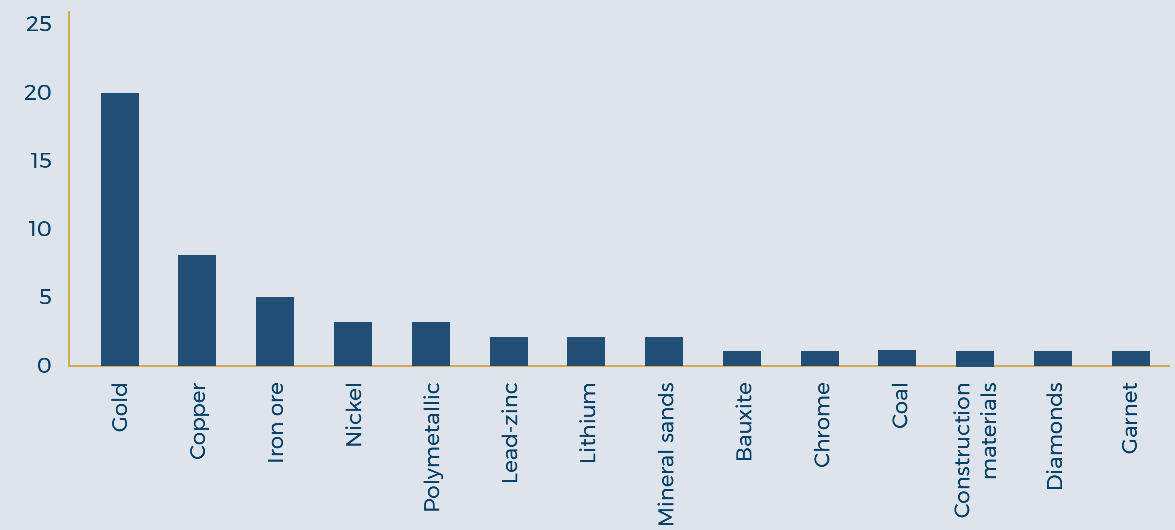
Figure 4 Growth in RE at mine sites since 2008



Source: compiled by the author

The gold sector has the highest number of RE sites, followed by copper and iron ore (see Figure 5). The latter is surprising given the large scale of most iron ore producers – copper mines are often large too, but many are located in Chile, where the government has made RE roll-out a policy objective.

Figure 5 RE installations at mine sites since 2008 by commodity



Source: compiled by the author

The future

In Ernst and Young's Top 10 Business Risks and Opportunities 2020 survey, obtaining a social licence to operate was the top ranked risk.[128] Reducing the operation's carbon footprint was ranked fourth. While obtaining a social licence has been a priority for some time (it was ranked fourth in 2017),[129] carbon is 'new to the radar'.

Mining Review Africa's 2019 survey[130] found that 43% of responding mining companies would use RE if it reduced costs; 35% if it reduced grid reliance; and 27% to lessen environmental impact. This paper has provided several citations in support of the steep and sustained decrease in the levelised costs of RE-generated electricity. In Figure 6, one of the reasons for this – increased generation efficiency – is shown graphically. It follows, therefore, that the uptake of RE by mining companies is likely to accelerate going forward. Increasingly efficient and affordable batteries will reinforce this – Bloomberg reports that the cost of lithium-ion batteries dropped by 73% between 2013 and 2019.[131]

The uptake of RE by mining companies is likely to accelerate going forward

The rise of EVs and the impending obsolescence of diesel trucks is likely to enhance the uptake of RE. EVs are much more efficient (long-haul electric trucks are 45% more efficient than internal combustion equivalents)[132] and the pressure to convert to EV haulage will mount. This will mean that more electricity will be required on site, and thus make it more likely that RE-generating capacity will be installed.

Another trend that is likely to increase the utility of RE on mine sites is the combined use of wind and solar. Hillig[133] reports increasing use of both solar and wind. Both of these are unstable sources but tend to be negatively correlated, so high winds often occur during periods of low solar irradiance (and vice versa). Consequently, use of both levels out the generation profile and reduces the required spinning reserve.

128 Paul Mitchell, "Top 10 Business Risks and Opportunities – 2020", EY, January 2020.

129 EY, *Top 10 Business Risks Facing Mining and Metals – 2016–2017*.

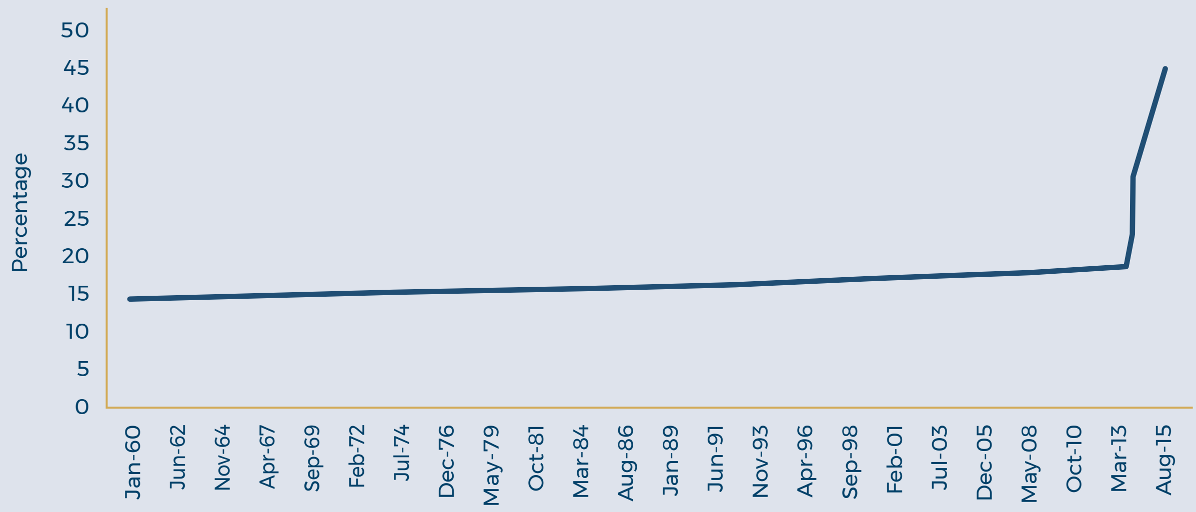
130 Gerard Peter, "Why Renewable Energy Makes Sense for Mining", *Mining Review Africa*, September 26, 2019.

131 Wes Doane and Jim Greenberger, "Top 5 Energy Trends of 2019", Power, October 27, 2019.

132 Thomas Earl et al., "Analysis of Long Haul Battery Electric Trucks in EU: Marketplace and Technology, Economic, Environmental, and Policy Perspectives" (Proceedings, 8th Commercial Vehicle Workshop, Graz, May 17–18, 2018), 22.

133 ThEnergy, "Renewable Energy and Mining".

Figure 6 Improvements in PV panel efficiency



Source: EnergySage, "How Has Solar Panel Cost and Efficiency Changed over Time?"

In addition to cost advantages, the benefits of RE include lower environmental impacts and higher levels of safety.[134]

RE holds advantages for national development. Zambia is an example of a country highly dependent on hydropower, which is becoming less reliable in the face of climate change, and expensive imported coal-generated electricity. Power outages are forcing Zambian mines to investigate alternative energy sources, since imported fossil fuels have historically been disadvantageous owing to the high transport costs – Zambia is landlocked. RE, in the form of solar PV, is likely to provide a complementary energy source, which, if installed by the mines and grid connected, may deliver a much needed boost to the Zambian economy. Chile, similar to Zambia in that it is a major copper producer with limited domestic fossil fuel resources, is an example of a mining jurisdiction that has assessed the risks of business as usual. In January 2011 it had an installed RE capacity of 591MW (3.8% of the energy mix). Five years later it had 3 793MW (17%).[135]

RE holds advantages for national development

134 Fleet et al., "Prospects for Renewable Energy".

135 Nasirova and Agostini, "Mining Experts' Perspectives".

Mines are moving away from grid dependence

In South Africa mines are moving away from grid dependence. Anglo American has made an application to the South African government to self-generate 75MW of solar power at Mogalakwena Platinum Mine, and Gold Fields' South Deep Mine has applied for permission to generate 40MW of solar power.[136] The Minerals Council South Africa reported that the industry has 1.5GW energy projects in the pipeline over 9–36 months. This trend is not restricted to countries that already have exposure to RE: India is targeting 100GW of solar PV by 2022.[137]

Conclusion

RE has gone from being a niche power source for small, remote mine sites to one of the most low-cost energy sources for large-scale mines, even when they are already grid connected. It is now a viable way of diversifying energy supplies and reducing price volatility. RE costs less than either grid or diesel power over a 20-year period and should be promoted as part of improving extraction efficiency in the minerals sector. PV, the most widely used form of RE, is increasingly portable and can be moved to another site on mine closure. Greater emphasis on the development of portable/mobile PV systems is required to facilitate uptake in the minerals sector.

RE has gone from being a niche power source for small, remote mine sites to one of the most low-cost energy sources for large-scale mines, even when they are already grid connected

As input energy requirements increase with decreasing grades and commodity prices trend downwards, energy innovation will be unavoidable. This, coupled with growing acceptance of novel technologies in the mining sector and RE's established role in sustainable development and climate change avoidance, will make RE increasingly attractive. RE's potential to drive down energy costs in the long term appears to be

136 Chantelle Kotze, "Details of Mantashe's Mining Power Generation Concession Still Missing", *Mining Review Africa*, March 3, 2020.
137 Fitch Solutions, "Shift to Renewables".

established. Mining companies will be able to claim a leadership position in many countries as they transition to new energy sources.

Tertiary educational institutions should develop RE-focussed courses to provide the numbers of skilled technicians and engineers required to support the expansion of the RE sector. RE systems for community and/or utility use should be considered as part of post-mining planning – these systems are a way of generating sustainable benefits for communities from degraded land. A caveat to bear in mind is that the energy density of the dominant forms of RE, PV and wind is low. Large land areas will be required to completely replace traditional power sources. Post-mining land will need to be used for RE generation, and energy efficiencies in mining and mineral processing will need to improve.

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Cover image

View of a floating solar plant of 256 photovoltaic panels installed on a floating platform on mine tailings of the mining company Anglo American in Colina some 35 km north of Santiago, Chile, March 14, 2019 (Martin Bernetti/AFP via Getty Images)

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