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Geothermal Energy in Mining Developments: Synergies and Opportunities Throughout a Mine's Operational Life Cycle

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ABSTRACT

Mines are heavy energy consumers and energy costs are significantly high for remote mines located far from the grid, due to considerable spending on fuel and fuel transportation. The mining industry is also increasingly aware of the need to shift towards cleaner energy sources in order to reduce its environmental impact. As a reliable source, capable of delivering very high availability factors, geothermal is an important, though often overlooked, energy option for the mining industry. For mines that are located in areas of high geothermal potential, geothermal energy can provide for parts of a mining operation’s electrical power needs. Geothermal fluids are utilized in a variety of ways during the operational life cycle of a mine. In the production stage, hot fluids are used directly in applications such as raffinate heating in copper production and enhanced heap leaching for the extraction of gold and silver. Underground mines in areas of high geothermal potential must deal with higher ventilation loads; these can be partially provided for by in-situ geothermal power generation. Geothermal fluids can also provide energy for space heating, typically a substantial load for northern mines. In the closure and post-closure phases of a project, hot water irrigation can enhance reclamation rates, while an operating power plant that is turned over to the local community results in jobs creation, and can support community development through projects such as geothermal district heating. In addition, geothermal energy helps reduce a mine’s environmental impact and Greenhouse Gas (GHG) emissions and improves its reputation within local communities, while “greening” its portfolio and contributing to sustainable development and the process of acquiring and retaining a social license to operate. The main factors affecting the successful integration of geothermal energy in a mining development are: the presence of a proven, accessible, and extractable resource; the relative price of alternate energy options; the distance from/to the grid; the potential for coproduction and/or minerals extraction; and the availability of communities and other industries in the vicinity of the mine. This paper outlines the synergies between mining and geothermal energy, and explores the ways in which geothermal energy can contribute to the development and operation of a mine.

1. INTRODUCTION

Mines are heavy energy consumers. They require energy to locate, extract, process and transport mineral resources to market. They require energy to sustain operations, provide safety and security, mediate environmental risks and close a project at the end of its life cycle (Newfoundland & Labrador 2012).

The life cycle of a modern mine can be divided in five distinct stages: prospecting, which is the search for ores and other minerals; exploration, i.e. the process of determining as accurately as possible the size and value of a mineral deposit; development, which consists of environmental permitting, designing, financing and opening a mineral deposit for exploitation, either by stripping the overburden or by underground mining; exploitation or operations, i.e. the actual recovery of minerals from the earth in quantity; and finally closure and reclamation, which includes closing a mine and recontouring, revegetating, and restoring its water and land values. Reclamation is a relatively modern (1970 and onwards) addition to the mine life cycle, brought about by the increasing demands of society for a cleaner environment and the stricter laws regulating future uses of mine lands. It follows an overall sustainable development approach around the concept of achieving "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*.” (Brundtland 1987; Hartman and Mutmansky 2002)

Mine energy use is very site-specific, as it depends on the mine’s location, the type of mineral resource in production and the extraction and mineral processes involved. Energy is purchased directly as electricity from the grid (if possible), as fuel to run combustion-based equipment (e.g. transport vehicles and ore processing equipment), and for environmental control through the heating and cooling of water and air (e.g. for mine ventilation, tailings treatment, and space heating/cooling). Different mine life cycle stages require different types of energy input but, generally, development and operations are the most energy-demanding mine life cycle stages. Canadian mines have in the past used diesel, gasoline, natural gas, explosives, light fuel oil and Bunker C fuel oil to conduct operations, including (but not limited to) drilling, blasting, mucking, loading/excavating, underground and over-ground ore transport, crushing, grinding, hoisting, ventilation, dewatering, separation, floatation, mill/space heating and lighting, and tailings disposal. This is on top of the more general heating, lighting and other electrical needs for mine facilities and camps (NRCan 2005a; NRCan 2005b).

Off-grid mines that are not connected to an electric power transmission and distribution network rely heavily on such conventional energy sources to meet their needs. Northern mines are particularly susceptible, as they are typically remote and cannot rely on future transmission grid expansions. Their total dependence on fossil fuels often comes with a high cost and risk. For example, the Diavik Diamond Mine lies about 300 km NE of Yellowknife, in the Canadian Northern Territories, and it is home to 1165 workers. Diavik’s remoteness and operating temperatures at arctic conditions (-30°C) make power security a critical safety and economic priority. Up until September 2012, the mine relied exclusively on 70 million litres of diesel, shipped over ice roads during a 6-week winter road season. Energy costs constituted more than 25% of the cost of mine operations, which were conducted under the increasing threat of climate change (directly affecting the short refuelling time window), very high fuel pricing and fuel volatility (Van Wyk 2013).

Cost and risk reduction are top priorities for any mining operation and mining companies are taking a long hard look at alternative, renewable energy options in an effort to shift away from a total dependence on fossil fuels. For Diavik Mine, the alternative solution most fitting to their needs and local resources was in the form of a wind farm. Operational since September 2012, the four 2.3 MWe wind turbines are expected to provide 17 GWh of renewable energy per year, corresponding to a 10% reduction in diesel consumption and a 6% reduction in GHG emissions (Van Wyk 2013). Much further to the south, Codelco, the largest copper producer in Chile, has a concentrated demand for process heat. The mine relies exclusively on diesel fuel to heat water, in the 50-60℃ range, for its copper electro-winning process, which yields a final product that is 99.999% pure. By replacing 85% of diesel consumption with 51,800 GWh of thermosolar, Codelco is expecting annual energy savings equivalent to the cost of almost two months of fuel (Judd 2013a; Judd 2013b). Newmont's projects in Ghana are almost exclusively hydro-powered and are proving more cost-effective than gas-fired or diesel plants. The same developer uses biodiesel at its Peruvian mines and to run trucks and cut costs in Nevada (CleanEnergyBC 2013).

The emerging shift towards alternative energy sources is not surprising; most are clean, locally produced and renewable. Geothermal energy offers the additional advantages of very high capacity factors (85-90%), very low environmental footprint in terms of land use and GHG emissions, and the ability to generate base load power, a characteristic of particular importance to the, typically, round-the-clock mining operations (Kagel and Gawell 2005; Li 2013).

2. MINES, ENERGY & DECISION-MAKING

In order to review how geothermal energy relates to mining operations, it is important to understand how mining companies make decisions on energy issues.

Operating costs: Mines operate to make profit, which is achieved either by reducing expenses or by improving production efficiency. With sustained commodity price drops, international competition and low profit margins, operating costs can have a significant effect on a mine's ability to survive market volatility. Sudden, steep drops in commodity prices have led to mine closures, as further production is deemed uneconomical. Mining operators are therefore constantly on the outlook for even marginal efficiency increases and cost reductions.

Access, safety, and power supply security: Remoteness, physical ease and safety of site access, connectivity to the electricity transmission and distribution network, availability and price of alternative fuel options, and fuel transportation costs are some additional risk factors affecting fuel source selection. Fossil fuels derived from regions of political turmoil and strongly controlled pricing by oil cartels can result in supply chain interruptions. In a world of political and environmental uncertainty, short-term energy-supply security and long-term energy independence are of paramount importance, and cannot be achieved without access to locally-produced, predictable and reliable energy (KPMG 2001).

Environmental requirements: Modern legislation dictates that resource extraction must be undertaken in a manner that does not interfere with the integrity of the environment, in terms of pollution control, remediation and resource conservation. The potential environmental impact from mining activity includes erosion, soil, groundwater and surface water contamination, loss of biodiversity, destruction/disturbance of ecosystems and habitats, GHG emissions, and large-scale land stripping (Azcue 1999). Adherence to environmental laws and regulations is seldom optional in developed countries. For example, Taseko Mines Ltd. new Prosperity open-pit gold and copper mine project near Canada's Fish Lake, B.C., has been twice rejected by the federal Ministry of Environment. An independent environmental review panel, fully supported by the local Tsilhqot'in Nation leadership, deduced that the project was likely to cause irreversible environmental damage to the Fish Lake water supply – a failed attempt that cost Taseko $110 million in prefeasibility costs. This kind of political pressure from environmental advocates and aboriginal groups helps to further underline the mining industry's need to control pollution and shift towards a cleaner operation. (Klein 2011; CBCNews 2013; CBCNews 2014)

Acquiring and retaining a Social License to operate: A mine's "Social License to Operate" defines the relationship between a mining company and the mine project's network of stakeholders (particularly the local community), that allows it to begin and sustain operations on a particular project. It is considered "an essential requirement for the future survival of the mining industry" (Thomson et al. 2012). In order to acquire a Social License, mining companies must demonstrate three key characteristics: a) social legitimacy, achieved through engaging with all members of the community and satisfying the communities need for information on the project; b) credibility, established and maintained through the application of formal agreements, keeping true to the promises and commitments made to their stakeholders; and c) trust, which requires companies to "go beyond transactions with the community and create opportunities to collaborate, work together and generate the shared experiences within which trust can grow"(SocialLicense.com 2014). The importance of acquiring and retaining a Social License cannot be overstated; failing to do so may result in non-starting or halting existing operations; for example, Taseko's apparent failure to acquire a Social License is evident by the strong opposition of some First Nations to the Prosperity project. Public and government concern about climate change is seen as a threat to the mining industry's ability to acquire and retain Social Licenses. Renewable energy's reliability, competitive pricing and reduced emissions can help mitigate such concerns, while contributing to the mine's reputation with its host communities, which "is crucial for obtaining and maintaining a social licence to operate" (Tuck and Helen; Connor et al. 2009; Simpson 2013).

SUSTAINABLE DEVELOPMENT

Akin to the concept of Social License, is that of sustainable development. The shift in public opinion towards mitigating humanity's impact on the environment, and looking past the short-term rewards of a project, product or activity, is also influencing the public's perception of, and expectations from the mining sector. As a result, and in keeping with the three requirements for acquiring and retaining a Social License – namely legitimacy, credibility and trust – mining operators are beginning to embrace sustainability as a strategic driver, and to work towards making organizational and operational culture changes that align with it. At its simplest level, sustainable development is a pattern of social, environmental, and economic growth (Figure 1). These three dimensions intertwine to define the many processes and pathways (such as sustainable material supply and consumption, good governance, and education) that lead to sustainability, i.e. the long-term end goal of creating a "paradigm for thinking about the future in which environmental, societal and economic considerations are balanced in the pursuit of an improved quality of life" (UNESCO 2014).

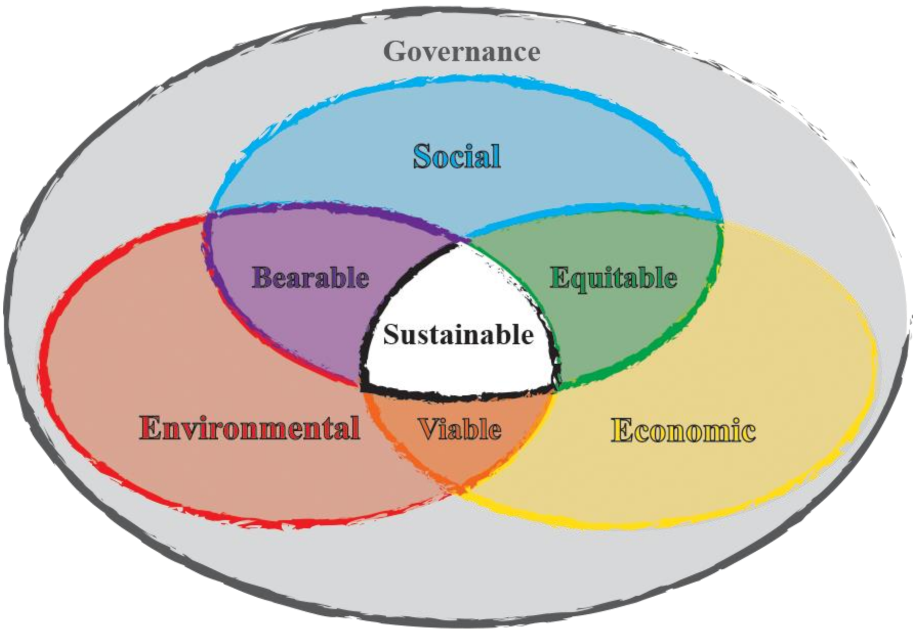

Figure 1: The four dimensions of sustainable development. Adapted from (Higgins 2013).

Mining and sustainable development

In 1999, some of the world's largest mining companies took on the "sustainable development challenge" by undertaking a global review of practices related to mining and minerals. The Mining, Minerals and Sustainable Development (MMSD) project was completed by the International Institute for the Environment and Development (IIED) in 2002 (refer to the final report – Breaking New Ground). One of the large number of projects prepared under the MMSD project had as its objectives to define a set of practical principles, criteria and/or indicators to assess how a mining/mineral project or operation contributes to sustainability throughout its entire life cycle. This undertaking eventually culminated in the definition and adoption of the Seven Questions to Sustainability (7QS) framework, designed to address whether a mining project is contributing to sustainable development in seven areas (MMSD North America 2002):

(1) **Engagement**: *Are engagement processes in place and working effectively?*
(2) **People**: *Will people's wellbeing be maintained or improved?*
(3) **Environment**: *Is the integrity of the environment assured over the long term?*
(4) **Economy**: *Is the economic viability of the project assured; will the community and better off as a result?*
(5) **Traditional and Non-Market Activities**: *Are traditional and non-market activities in the community and surrounding area accounted for in a way that is acceptable to the local people?*
(6) **Institutional Arrangements & Governance**: *Are the rules, incentives, programs and capacities in place to address project or operational consequences?*
(7) **Overall Integrated Assessment & Continuous Learning**: *Does a full synthesis show the net result to be positive or negative?*

A net positive contribution to sustainable development can only be achieved by fully committing to support and foster continuous environmental and socio-economical improvement, through the whole mine life cycle, from exploration to closure and post-closure. This requires forethought, with mining operators addressing environmental and social problems at the source, rather than after they happened (Hilson and Murck 2000). Energy is one of the major aspects that must be considered in this process.

3. MINING AND GEOTHERMAL

Central to the argument that geothermal is a highly attractive energy option for mining operators are the many characteristics, resources and processes shared by the two industries, as discussed below.

Basic definitions

Mining or *mineral resource extraction* is the process through which economically valuable mineral resources, namely *metals* (including: ferrous metals, such as iron, manganese and tungsten; *base metals*, such as copper, lead and zinc; and *precious metals*, such as gold, silver and platinum), *non-metallic/industrial minerals* (i.e. *nonfuel mineral ores* that not associated with the production of metals, such as phosphate, limestone, and sulfur), or *energy minerals* (e.g. *fossil fuels* such as coal, petroleum, and natural gas, and uranium), are identified, located, extracted, and processed, for their subsequent use in consumer products (Hartman and Mutmansky 2002). Correspondingly, *geothermal energy* production can be defined as the process through which economically valuable hot geothermal fluids are identified, located, extracted and processed, for their subsequent use in electricity generation, or in direct, non-electric applications (Dickson and Fanelli 2003). In this analogy, the extraction of geothermal fluid is seen simply as another mining project, with heat replacing mineral fuels as the economically valuable resource.

Mining and geothermal production also share a dependence to the concepts of *accessibility* and *extractability*. Mineral deposits must have sufficient economic value to be mined at a profit. This means that the ore must be of sufficiently high grade, it must be located in a physically accessible location and at practically attainable extraction depths, and it must be extractable at an economically viable extraction cost (American Geological Institute 2003; Johnson et al. 2010; Johnson et al. 2011). In geothermal production, it is the fluid's heat content (expressed as enthalpy), accessibility (in terms of practically drillable depths), and extractability (in terms of achievable mass flow rates from a given well) that determine whether a geothermal resource is economically valuable and warrants production (DiPippo 2012).

Mining, heat, and water use

Heat and water are cardinal elements of geothermal systems. They also play a key role in mining and mineral extraction. As a transport medium, water mixes with crushed ore to produce ore slurry that can be piped through for processing in a more efficient and economic manner to trucking or hauling. As an excess by-product in pits and underground tunnels however, it can disrupt access to the mine workings, and must therefore be removed (International Council on Mining and Minerals 2012). Heat addition to specific mineral processes can significantly enhance yields and production efficiencies. Conversely, excessive heat flow in underground mine galleries located in areas of adverse temperature gradients constitutes a safety hazard for mine workers, and must be continuously cooled and ventilated at a correspondingly higher operational cost.

Heat recovery is only valuable if the recovered heat can be reused. Through careful whole-system analysis and design, heat losses and water use can be monitored in order to balance loads, improve performance, decrease emissions and minimize waste. For a mine with access to low-temperature geothermal resources, the addition of waste heat recovery either from exothermic mineral processes or high-load ventilation and cooling systems, can further improve performance, efficiency, and cost-reduction. The captured heat can be stored on-site or used directly as process heat. For example, the Finish smelter operator Boliden Harjavalta Oy recovers 20 MWth of heat from its sulphuric acid plant; half of this heat energy is used in the company's adjacent copper and nickel plants, and the other half is sold to a local district heating network (AlfaLaval 2011). Alternatively, the recovered heat can be supplied to an Organic Rankin Cycle (ORC) heat engine to generate supplementary electricity; water with temperatures as low as 78℃ can be used as a heat source in this manner (Zarrouk and Moon 2014).

Co-occurring geothermal and mining resources

High-temperature geothermal systems are associated with volcanism and plate tectonic activity, with the majority of high-enthalpy geothermal resources occurring around the Ring of Fire surrounding the Pacific tectonic plate. About 10,000 MWe of geothermal power capacity has been installed almost exclusively in this region (Sanyal 2010). High-temperature geothermal reservoirs are also associated with high concentrations of hydrothermal alteration minerals, such as gold, copper and silver, due to the tendency of precious metals to precipitate and deposit in response to boiling and mixing of deep geothermal fluids (Browne and Simmons 2000).

The map in Figure 2 comprises of three data layers: one that maps world-wide open-pit and underground mining sites (USGS National Minerals Information Center); a second layer, gives smelter operations around the world (http://minerals.usgs.gov/minerals/). The third layer contains currently operational geothermal power facilities (http://thinkgeoenergy.com/, http://en.openei.org/, and web sites of individual power producers). Tectonic plate boundaries and volcanoes from around the world are also included (courtesy of the Smithsonian Institution, Global Volcanism Program), as indicators of high temperature geothermal potential.

Based on the density of the overlapping data, and under the hypothesis that concentrated activity corresponds to high potential (be it existing or future), six "hot-spot" regions can be identified as being more suited for development that integrates geothermal power/heat with mineral extraction. These are: **(A)** California and Nevada in the United States; **(B)** El Salvador, Guatemala, Honduras and Nicaragua in Central America; **(C)** Chile and Peru on the westernmost extent of South America; **(D)** The Republic of the Democratic Republic of Congo (DRC), Eritrea, Ethiopia, and Kenya, on the East African Rift; **(E)** The Philippines in the western Pacific region in Southeast Asia; and **(F)** the Taupo Volcanic Zone of the North Island in New Zealand. A short list of the co-occurring mining and geothermal resources is included in Table 1.

4. GEOTHERMAL APPLICATIONS AKIN TO MINING

Generally, it is fluid enthalpy (h) that determines (or limits) how the extracted geofluids can be used, and what their expected economic value would be. Resources on the highest end of the scale are typically employed in power generation: in dry steam power plants for dry or superheated steam sourced from dry-steam or vapour dominated reservoirs; in single- or double-flash steam power plants, for high- to medium- enthalpy fluids sourced from liquid-dominated hydrothermal reservoirs; and in binary cycle power plants, used with low-enthalpy resources, or as a supplementary stage to existing flash steam plants to recover power from hot, waste brine. With the exception of numerous industrial applications, low to very-low temperature fluids are generally reserved for direct use. The very end of the enthalpy scale contains geoexchange applications that use heat pumps to boost the amount of energy harvested from shallow to very shallow depths (<300 metres on average) (Curtis et al. 2005).

Figure 3 lists various examples of geothermal direct use applications that relate to mining activities, in order of decreasing temperature. The temperatures indicated on the color scale are approximate and correspond more to applicable temperature intervals, rather than absolute values – this is due to the fact that most geothermal applications, whether power or direct, are site- and case-specific. The diagram was modeled after Lindal (Thain et al. 2006).

Table 1: Inventory of high-opportunity areas: co-occurring mineral and geothermal resources

Region/Countries	Mining Resources/Activity	Geothermal Resources/Activity
A: West coast, USA	*California*: gold, serpentine, benitoite, silver, sand & gravel, salt potash, turquoise, zeolites, clay & shale, sulfur, salt, diatomite, boron, feldspar, perlite, soda ash, and talc. *Nevada:* gold, coper, lithium, molybdenum, diatomite, gypsum and lime.	*California:* 42 power plants producing a total of 2,500 MWe (= 4.4% of state total). Medium to high temperature resources. Geysers one of four dry steam reservoirs in the world. *Nevada:* 22 geothermal power plants producing a total of 586 MWe (= 7% of state's total). Low-medium to high temperature resources (95-250°C production brine). Currently holds largest amount of untapped resources in the US.
B: Central America	Gold, tungsten, antimony, nickel, silver, zinc, lead, copper, quartz, iron, manganese, mica, chromium, gemstone, diatomite, marble, feldspar, bentonite, barium-barite, asbestos and mercury.	Total install capacity ~500 MWe: El Salvador (204 MWe), Costa Rica (163 MWe), Nicaragua (87 MWe), and Guatemala (49.5 MWe). Untapped power potential ~3,000 - 13,000 Mwe.
C: Chile/Peru	Copper, gold, silver, manganese, lead, zinc, molybdenum, cobalt and nickel.	*Chile:* Vapor dominated system at 230-240°C (reservoir). Currently under advanced exploration. Estimated generation potential of 16,000 MW for at least 50 years, for fluids at >150°C, extracted from < 3,000 m depth. *Peru:* Estimated generation potential of 600-1,410 MW.
D: East African Rift	Copper, cobalt, platinum, gold, nickel, chromium, clay, granite, limestone, marble, salt, sand & gravel, zinc, soda ash, tantalite, diatomite, graphite, tungsten, irona and asbestos.	Total estimated potential of 15,000 MWth of heat and 2,500 MWe for power. *Kenya*: Total installed geothermal capacity (Olkaria I, II & III) of 250 MWe. *Ethiopia*: Current installed capacity of 7 MWe, with expansion plans to 70 MWe.
E: The Philippines	Nickel, cobalt, coal, copper and gold.	The world's second largest producer of geothermal power with installed capacity of 1.9 GWe (= 17% of overall national). Currently untapped geothermal potential estimate at 2,600 MWe.
F: North Island, New Zealand	Iron, coal, gold and silver.	Installed power capacity of about 750 MWe (= 13% of national). Untapped geothermal power capacity estimated at 1,000 Mwe.

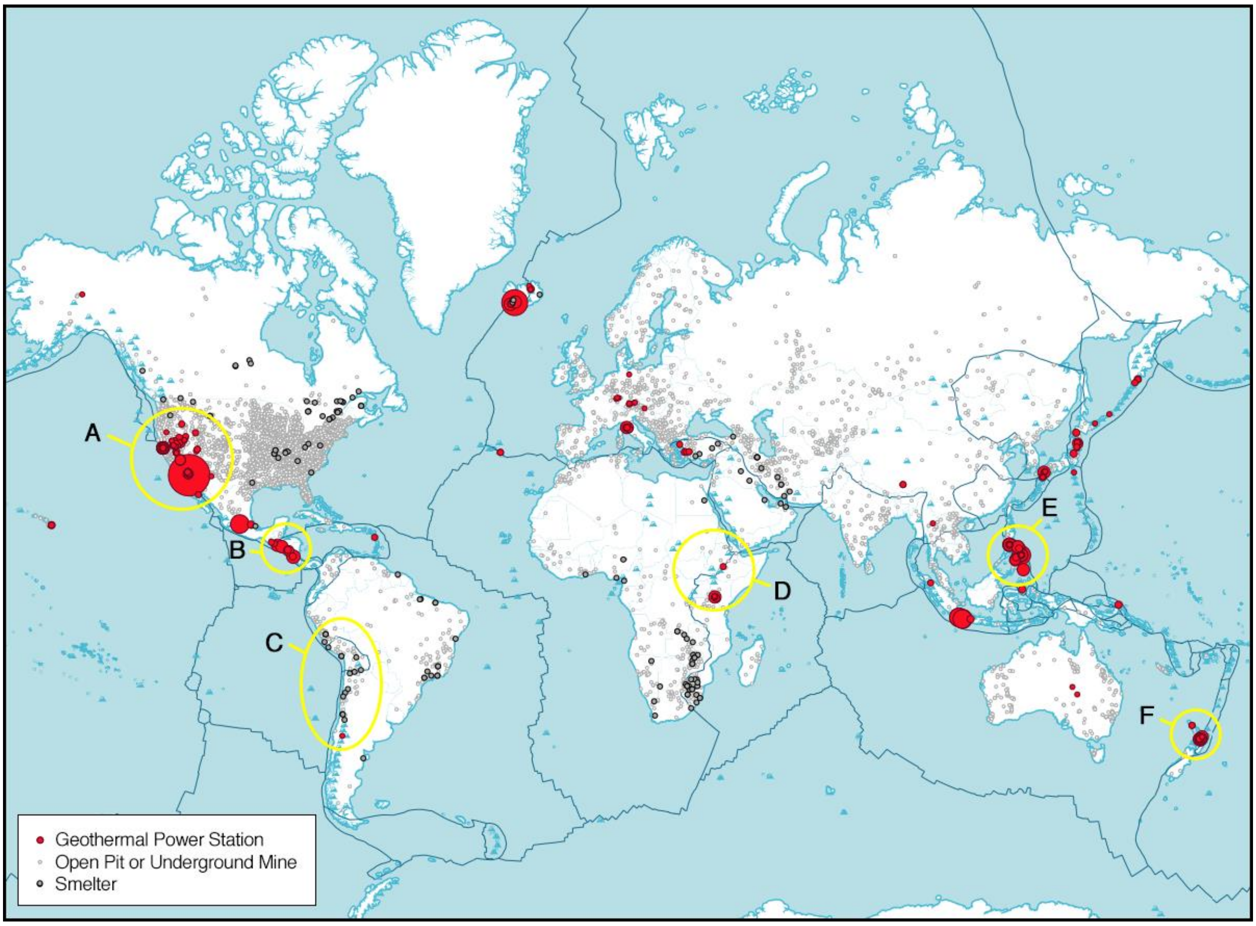

Figure 2: Map overlapping mining operations and geothermal potential on a global scale.

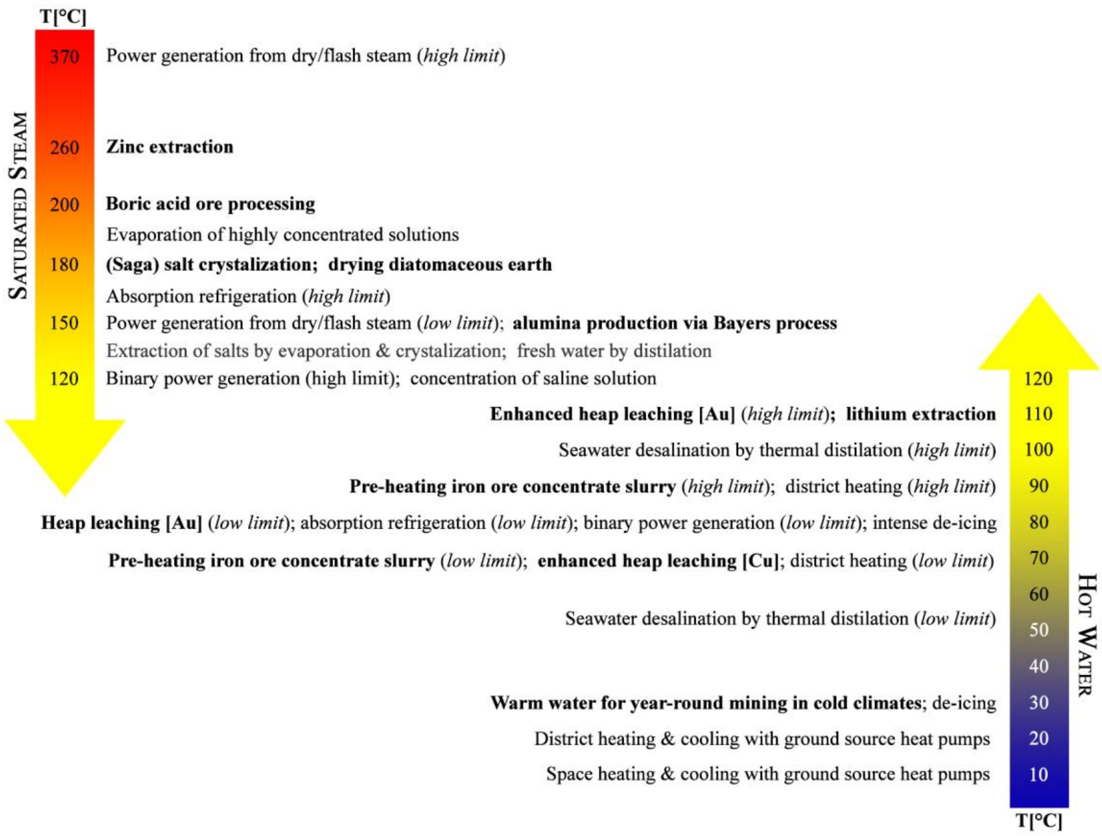

Figure 3: Geothermal use for the mining sector (modelled after Lindal) (Thain et al. 2006)

Power production/supplementation for remote mines

It is not only mines in the far North that worry about fuel supply. More that 4 km high up the Andes Mountains, in the San Juan Province of Argentina, lays Veladero gold mine (29.350494°S, 69.983254°W) (see Figure 4). In production since 2005, Veladero has 5.1 million oz. of estimated gold reserves.

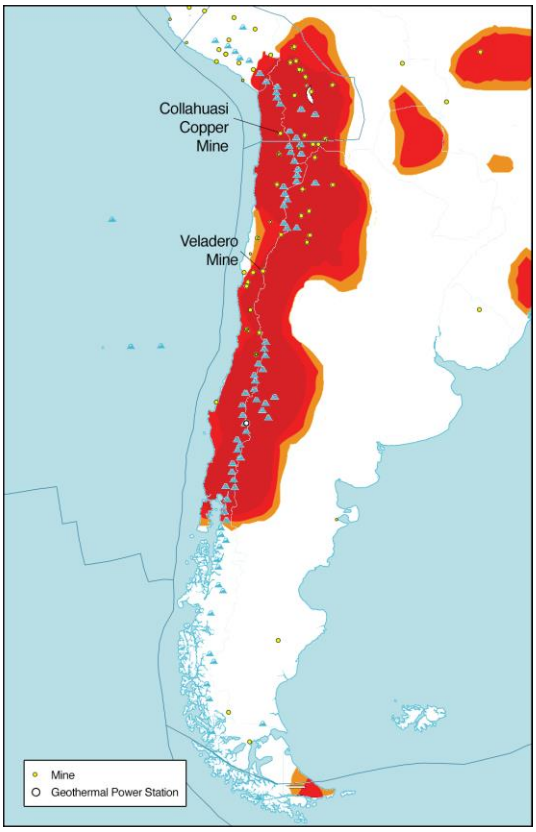

Figure 4: Mines and estimated heat flow in Peru, Chile and Argentina, as given by Hamza et al. (2010)

Currently, the mine consumes about 30 million liters of diesel fuel to generate the 12.5 MWe it requires to operate. Seventeen tanker trucks travel 500km every week to transport this fuel to site. Gold – a hydrothermal (epithermal) alteration mineral – is closely associated with geothermal energy. Medium-low geothermal resources have been found onsite, with surface thermal springs up-flows measuring between 76-78°C. The operator is looking at an estimated 8-14 MWe binary plant installation that will run on geofluids sourced from 1-1.5 km depths. The proposed plant will have enough capacity to cover 66-100% of Veladero's operational needs, and it is expected to generate annual savings of 19-30 million litters in fuel consumption and 53,000-93,000 tons in GHG emissions. The operator cites geothermal energy's 24-hr availability (ideally suited for the mine's around the clock operation) and reduced fuel transportation costs as the reasons behind the decision to invest up to $12 million on geothermal exploration and potential assessment. (Borders 2013; BarrickGold 2014)

Minerals Extraction

The chemical composition of geothermal fluids varies greatly between reservoirs. Rock composition, temperature and pressure at depth all affect the eventual fluid mineral composition. Rich brines, though more difficult to handle in the power production process, can extend the economic value of a resource through the exploitation of the primary power generation by-products, such as various water-soluble minerals and precious metals. Actually, the higher the chemical concentration, the more minerals could be potentially extracted from a given brine. In some cases, extracting a mineral from geothermal brine may be more economically attractive than mining it from rock (Bakane 2013).

Silica

Silica, as the most abundant mineral in geothermal brine, typically interferes with electricity generation by precipitating from solution and adhering to pipe and equipment walls. It therefore needs to be removed. The extraction process employed for this purpose will determine the particle size of the extracted silica, and hence the quality of the end marketable product. The smaller the particle size of the silica, the higher its quality and value, but the harder it is to produce. At present, silica extraction purity is close to 99% (Bourcier et al. 2006).

In Mammoth Lakes, California, marketable amounts of quality silica are extracted from the geothermal brine that is supplied to the Mammoth Pacific power generation plant. Mammoth uses reverse osmosis to produce very high quality silica, mainly due to the field's very low salinity, very low calcium, negligible iron, and other heavy metals content. Bloomquist (2006) evaluated the annual yields at $11 million, based on the typical market price $0.75 per pound for precipitated silica used in rubber manufacturing, and a silica recovery of 7,200 tons per year. The Mammoth brine also contains extractable lithium, tungsten, cesium and rubidium (Bloomquist 2006; Bourcier et al. 2006).

Lithium

Lithium (Li) is used in a broad spectrum of products and industrial applications, including but not limited to batteries, ceramics, glass, rubber, lubricating greases, pharmaceuticals, and in primary aluminum production. It is more stable when processed into compounds such as lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH), and it is primarily produced in Chile, Australia, China, and Argentina, either from hard-rock, open pit or underground mines, or through solar brine evaporation. Although current (2013) demand levels – at 160,000 tonnes per annum – are lower than the estimated word production levels – at 186,000 tonnes per annum – the US Department of Energy (DOE) lists lithium as a strategic mineral and predicts a 60% market growth by 2017, driven by the high tech and automotive industries (U.S. Department of Energy 2011; Kaufmann 2014).

Simbol Materials demonstration plant in Calipatria, CA is developing an alternative, high quality, lithium extraction process to use with Salton Sea's geothermal brine, one of the most concentrated mineral brines in the world (with a mineral content ranging between 200,000 – 250,000ppm). The lithium-bearing brine is sourced from EnergySource's Featherstone 50-MWe geothermal power plant, at a flow rate of 6 gal/min and at an outflow temperature of 110°C. Extraction is completed in stages, first by removing the silica (SiO_2), then iron (Fe), and finally lithium carbonate, which is the primary product in this process. Three additional to silica and iron by-product minerals will also be extracted at full-scale production, namely manganese (Mn), zinc (Zn) and potassium (K). When operational, the full-size plant will be able to handle 1000 times the demo plant flow rate, generating 16,500 tonnes of high-grade lithium per year – currently valued at $6,000 per tonne – from an average brine input of 6,000 gal/min (Duyvesteyn 1992). In fact, the economic value of the Salton Sea minerals is estimated at $1.5 billion dollars. This is higher than the economic value of the net combined 327 MWe produced by the 10 power plants operating in the Salton Sea Known Geothermal Resource Area (KGRA). Full-scale production yields from the Featherstone plant are estimated as: 16,000 tons of lithium carbonate equivalent, 24,000 tons of electrolytic manganese dioxide, and 8,000 pounds of zinc metal (Harrison 2010). According to the DOE, Simbol's business model separates the geothermal operator from the business of mineral extraction, thus reducing risks and costs (Klein and Gaines 2011; CalEnergy 2014; Kaufmann 2014).

Enhanced heap leaching

(Hartman and Mutmansky 2002) define heap leaching as the process of recovering minerals from typically low-grade metal ores with copper, gold, or uranium content; this is achieved through the application of an aqueous leachate solution on piles of broken ore stacked on impermeable pads. The leachate solution impregnated with the extracted metals is collected as it percolates out from the base of the heap and further processed to produce doré (a semi-pure alloy of gold and silver), prior to being transported to a refinery for further purification (Kappes 2002).

Adding heat to the leaching solution in small-scale experiments accelerated the chemical reaction behind extraction, by improving the kinetics of the leaching process (Trexler et al. 1990). Also known as enhanced heap leaching, this process can increase gold extraction rates by 5-17% and copper extraction rates by 1.2% per degree Centigrade change in the heap solution temperature. Enhanced heap leaching also allows for year-round operation of a mine site, independent of weather conditions, as typically, heap leaching stops when temperatures fall below 4°C (Bloomquist 2006; Sigmundsson 2012).

In Nevada, a total of 10 producing gold, silver, or gold/silver mines have geothermal resources on-site or in close proximity to the leaching facilities. A number of them are already using geothermal brine in enhanced heap leaching (Figure 5). At the Round Mountain Gold mine, 82°C geothermal fluid is fed through counter-flow heat exchangers at an average flow rate of 70 L/s to heat the cyanide leach solution. The system has an installed capacity of 14.1 MWth and uses the equivalent of 42 TJ of thermal energy per year (Lund 2003). Annual production levels at the Florida Canyon mine are 905 kg for gold and almost 800kg for silver (Driesner and Coyner 2007). The heat is transferred from geothermal fluid at 99°C to the barren cyanide solution using a shell and tube heat exchanger (Trexler et al. 1990). The 1.4 MWth system uses an estimated 42 TJ per year (Lund 2003). In the past the gold-producing Freeport Jerritt Canyon Mine and the silver-producing Gooseberry Mine also used thermally-enhanced cyanide heap-leaching process (Flynn et al. 1986; Bakane 2013).

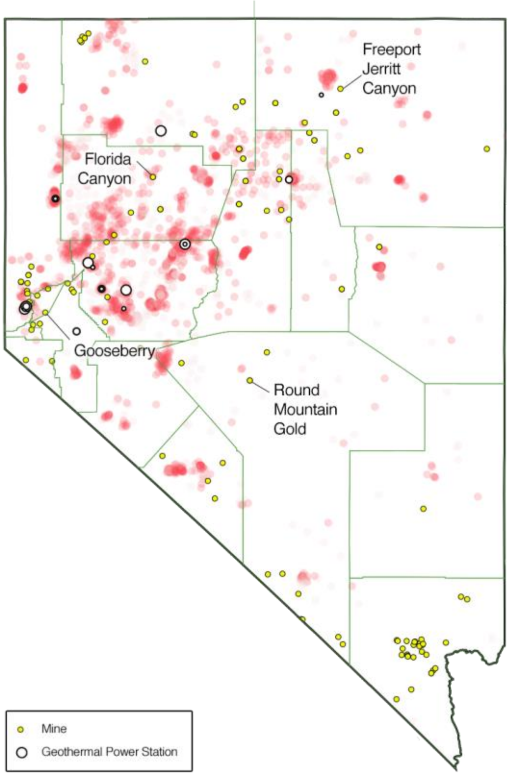

Figure 5: Mines, geothermal power stations, and heat flow measurements in Nevada.

Sigmundsson (2012) investigated the potential advantages of using low-temperature geothermal fluids in heap leaching for copper, at Chile's Collahuasi Copper Mine (see **Error! Reference source not found.**Figure 6). Currently, the mine can extract about 40% of the copper contained in its ore heaps. An acidic mixture of water and sulphuric acid (termed raffinate) is used as the copper-bearing heap leaching solution. The extraction process comprises of heating the raffinate from 15°C to 35°C using diesel oil and propane, prior to re-circulating it to the heap pads. The study indicated that using 70°C geofluid as the primary heat source in a geothermally-enhanced heap-leaching alternative would increase production levels by an average of 1.2% per degree Centigrade change in the raffinate temperature. The resulting fuel-cost savings for the proposed system upgrade corresponded to a 12-month projected payback period.

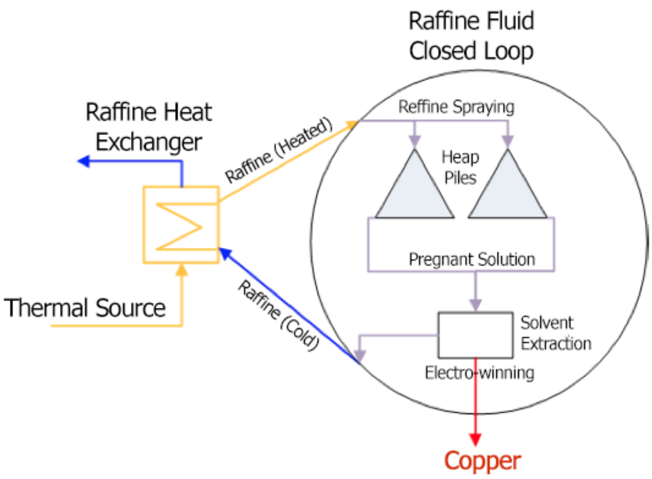

Figure 6: Enhanced heap leach system, Collahuasi Copper Mine (Sigmundsson 2012). Used by permission.

Desalination

The number of people working on a mine site varies from project to project but it can be in the thousands. As stated, the water used in some operations can potentially be of such low quality that it would not be suitable for human consumption, although that is not always the case. Nevertheless, for sites accommodating human workers, access to a potable water source is absolutely necessary, but not always easy to secure. A number of operators are resorting to desalination to meet this need.

In western Australia, CITIC Pacific Mining required a full-scale desalination plant – complete with water transmission lines – for transporting iron ore slurry at their Sino ore project mine site. The amount of water to be generated every day was 140ML, enough to fill 56 Olympic-sized swimming pools. With fresh water demand for copper production on the rise (expected to increase by 38%

by 2021), Chile is pushing hard to make desalination in mining processes mandatory, for mines consuming more than 150 L/s. A number of companies have already introduced desalination plants into their operations, for example BHP at Escondida (24.266667°S, 69.066667°W), Freeport-McMoRan at El Abra (21.916667°S, 68.833333°W), and Coldeco at their Radomiro Tomic (22.2167°S, 68.9000°W) and Chuquicamata (22.289444°S, 68.901111°W) divisions. Salt removal in Chile has become increasingly costlier in recent years (amounting to US$5/m^3 versus US$2.8/m^3 in Mexico), and a mandate to desalinate will directly impact operational costs and profit margins (Jamasmie 2014).

Mines with access to geothermal resources may have the option to use it for desalination. A demonstration/research project on the Greek island of Milos (36.681684°N, 24.457568°E) used geothermal brine to run a seawater desalination unit. The developed device, successfully separated seawater into two streams of potable, low-salt-concentration water, and highly concentrated salt brine. Four production wells providing 300 m3/hr of geothermal fluid at 55-99°C, can be used to thermally distil, in stages and under pressure, seawater at 80,000ppm salinity. This system has a production capacity of 75-80 m^3/hr of drinking water, enough to cover the needs of the entire island at an estimated cost of €1.5/m^3. The harvested heat would also be enough to generate a supplementary 470kWe of power using an ORC unit (K4RES-H 2010).

There is an additional, socioeconomic aspect to desalination plants: though built as part of a mining development, they can simultaneously supply potable water to adjacent communities with fresh water needs: Areva's Trekkopje uranium mine (22.450000°S, 15.033000°E) in Namibia is doing just that, all the while positively contributing to the region's sustainable development (UGL Ltd. 2009).

Mining areas of high geothermal potential

In certain cases, high geothermal potential can actually act as a hindrance to mining activity, in particularly underground mining. For example, Enterprise Mine (13.695910°S, 131.792928°E) is Australia’s deepest and hottest underground operation. A high grade copper mine, it extends from about 1000 m below the surface to almost 2000 m below surface. Below 100m, temperature almost always increases with depth and at Enterprise Mine, the extreme depth combined with a high geothermal gradient of 200°C /km, a surface rock temperature of 28°C and high surface ambient temperatures during summer, applies extreme heat stresses that must be managed for the safety of workers. Additional heat sources compounding on the problem include surface climate, autocompression, plant machinery and equipment, oxidation, explosives, broken rock, lighting, personnel and service water. Extreme heat has been linked to significant decreases in productivity, and high accident rates (Brake and Fulker 2000).

Typically, underground conditions are managed by ventilation, in a process that “floods” the mine with air to remove heat – which, in this context is regarded as an unwanted air-borne contaminant. But for mines that are deeper than 1000m, ventilation cannot provide adequate fresh air to the workings to removing heat, blasting gases and diesel fumes. In cases such as these, refrigeration is unavoidable; in fact, Enterprise Mine refrigeration needs exceed 40 MW(R) (Brake and Fulker 2000).

Space heating and cooling in operating mines

Most operating mines have onsite space heating and/or cooling needs, e.g. within administrative buildings or live-in camps. Very-low-temperature ground source heat pump systems (GSHP’s) generally operate within an average 5-25°C temperature envelope and have the potential to provide for this kind of need. GSHP’s use a binary fluid that has a very low boiling point (e.g. -26.3°C for tetrafluoroethane (R134a)) to transfer heat from source (e.g. the ground) to target (e.g. mine camp). The overall system comprises of 3 separate components: **1)** an open or closed loop installed in the ground or submerged in a large water mass, at depths of relatively constant temperature; **2)** a heap pump unit that supplements and boost the heat extracted from the ground with electricity; and **3)** a distribution system that uses air or water to transfer the heat at target. GSHP’s operate at very high efficiencies (300-600% or 3<COP<6) and vary in size from individual modular units used for single rooms, to district-sized units that can generate enough capacity to serve large communities – one such example is the case of Dalian, China, where 68MWth of total heating and 76MWth of total cooling loads are generated by a district cooling and heating seawater system, from source temperatures between 2℃ (winter) to 21°C (summer) (Patsa 2009). According to (Koufos 2012), Canadian mines stand to gain considerable energy savings by switching their space heating and cooling systems to GSHP's. Based on a study involving 12 mines across Manitoba, Ontario and Quebec, such a switch would result in total annual heat savings of 20,915 kWth, equivalent to CAN$1.5 million/year in cost reductions and 18,850 tonnes in CO_2 emission reductions. The systems examined in the study used water mined from depths between 800-3,100m as the source of heat, extracted at flow rates between 7-63 L/s, at source temperatures between 10°C and 22°C.

District heating & cooling from abandoned mines

More than 1 million abandoned mines are thought to exist around the world, some of them in close proximity to densely populated areas (Preene 2013). Although past their operational life, they still hold economic value - this time around, in the form of heat mining. Flooded underground mines are essentially large heat storage units. Depending on the depth of the mine and the local geothermal gradient, enough thermal energy can be extracted from the mine-works to supply a district-sized heating and cooling system, optionally coupled with GSHP's. The technological feasibility of this concept has proved successful: overall, more than 15 deployed project in Canada, the US, Germany, Norway, the UK, the Netherlands, Russia and Spain are utilizing mine water for heating and cooling (Preene 2013).

The Heerlen Minewater project in the Netherlands (50.889920°N, 5.979606°E), for example, was built as part of a regeneration scheme for an area that was devastated by the closure of coal mines. The system taps into heat stored in four flooded underground coal mines, and services 33,000m^2 of residential space, 3,800m^2 of commercial/cultural space, and 13,700m^2 in health care and educational institutions. Mine water is harvested from a depth of 700m, at 22 L/s, and passes through heat exchangers operating at a ΔT of 5°C. (Koufos 2012)

Further to the North, the British Geological Society is teaming up with Glasgow City Council, to look into the potential of heat mining, as part of the Clyde Urban (regeneration) Super Project. A heavy-industry boom in the 19th century and an abundance of coal and iron in the general Lanarkshire region, led to Glasgow's ascent as the world's preeminent shipbuilding centre. Now mostly defunct, the majority of these mines lay beneath the city. The project is looking at the potential heat within minewaters, superficial deposits and bedrock aquifers, and the feasibility of using it as a source for district heating and cooling. Geological modelling has identified a number of drilling targets, primarily within mine shafts that are most likely to be structurally preserved (British Geological Survey 2014; Wikipedia 2014).

Mines, carbon taxes and the Kyoto Protocol Clean Development Mechanism

Emissions savings are fast becoming a prominent concern of the mining industry, primarily due to an anticipated need to mitigate some of their emissions-related fees. Climate legislation, such as President Obama's Climate Action Plan in the US and Australia's Clean Energy Act 2011, is expected to have a considerable impact on operating costs across the entire mining industry. Operators that fail to reduce their greenhouse gas emissions will be required to pay carbon taxes and fines, and are therefore actively looking at clean energy for offsetting some of their operation-related emissions. Newmont Mining Corporation, concerned about potential carbon fees for its US and Australian projects, is taking advantage of the Kyoto Protocol Clean Development Mechanism (CDM), under which, "climate-friendly, sustainable development projects in developing countries are eligible for Certified Emission Reductions (CERs)" (UNESCO 2014). CERs define ways for governments and corporations to meet their compliance obligations, under cap-and-trade schemes pending in the U.S. and Australia. Newmont is positive that geothermal energy provides them with an opportunity to "not only reduce emissions and increase [their] energy efficiency, but also to earn CERs to use later in cap-and-trade schemes" (Newmont Mining Corporation, 2010). CERs developed prior to the deployment of a cap-and-trade scheme are expected to cost less than half of the same CERs purchased post-deployment (Hannam 2014; The White House 2014).

5. THE CASE OF LIHIR

The Lihir Gold Mine (3.129613°S, 152.630858°E) in Papua New Guinea (PNG) presents a fine example of integrating geothermal and mining activities. In production since 1997, it currently employs more than 2,200 people and has an annual production of 649,340 gold ounces (2013 figures). This mine is of particular interest: it is an active hydrothermal environment, with proven high-temperature geothermal potential onsite, and without access or proximity to a power distribution network (Bertani 2010).

Current production uses geofluids primarily extracted from a depth of 1,000 m at 240-250°C, but temperatures greater than 300°C have been measured. Four wells located on the property, initially drilled for the purpose of releasing ground pressures while open pit mining, supplied steam to a 6MWe non-condensing power plant, which was installed in 2003 (Bixley 2003). Two subsequent expansions – a 30MWe single flash, condensing geothermal unit 2005, and 20 MWe extension in 2007 – raised the total combined generation capacity to 56MWe. This power is generated for exclusive consumption at Lihir Gold and covers about 75% of the mine's power needs. 30MW are used by the oxygen plant, less that 3MWe are directed offsite for used in local villages, while the remaining capacity powers the mine, onsite camps and offices. Although secondary to the gold mining activity, the geothermal system has generated significant annual savings and revenues: US$40 million in savings from offsetting heavy fuel oil consumption (which corresponds to >50% of the mine's energy cost), and US$4.5 from sales of carbon credits on the global market. The plant's emissions savings actually correspond to approximately 280,000 tonnes GHG per year and allow it to trade carbon credits under the CDM. The operators also contribute to the broader PNG economy and local communities, through "taxation and royalties to national, provincial and local governments, salaries and wages, landowner contracts, investments in public infrastructure and services, and support of Lihirian and PNG suppliers, […] including access to health services, the provision of electrical power and water to local villages" (NewCrest Mining Ltd 2013; Melaku 2005). Finally, it is interesting to note that the incremental transition from diesel fuel to geothermal power (from 5MWe in 2003, to 35 MWe in 2005, and finally to 56MWe in 2007), allowed the company to gradually build its on understanding of the geothermal reservoir, and eventual trust in its potential.

6. CONCLUSION

This paper explores the great synergistic potential between geothermal energy and mining operations. Geothermal energy can be a source of power generation for mines that are located in areas with high geothermal potential. It may also be used in numerous direct use applications, such as: extracting minerals from brine; improving mineral processing efficiencies in heap leaching of gold, silver and copper; desalinating seawater for mine use; and for space heating – either during active mining or as part of a post-closure plan.

Factors that affect the integration potential of the two technologies/industries include: the physical remoteness of a mine site and by extension the local climatic conditions; the distance from and access to a power distribution and transmission network, and the price of purchasing and transporting alternate energy sources; the size and type of the geothermal resource available to the mine site, in terms of production enthalpy, achievable mass flow rates and brine mineral content, as they dictate the type of potential use (incl. co-production) and its economic value; the type of mining operation, and by extension its demands in terms of direct heat use, in mineral processing or for controlling working conditions on-site (e.g. for ventilation and/or space heating and cooling); the size and proximity of local communities that can use the produced energy, as part of a mine's sustainable development plan; and the importance that the operator puts on its in-house green energy culture and policy.

Ideally, geothermal energy would be most attractive to mines that: are in remote areas; without access to the grid; with known or proven, extractable, and accessible geothermal reserves; and a need or utility for direct heat. In any case, for mines located in areas of high potential, geothermal energy is an option worthy of consideration.

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