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SMRs for Mining

Opportunities and Challenges for Small Modular Reactors

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Nuclear Technology Development and Economics

SMRs for Mining: Opportunities and Challenges for Small Modular Reactors

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The mission of the NEA is:

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- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of NEA competence include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

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Foreword

The decarbonisation of industrial sectors is crucial to achieve global net zero emission targets and to ensure a sustainable future. As industries transition from fossil fuels to clean energy alternatives, the mining sector stands at a critical juncture. Mining is not only essential for producing the materials and critical minerals required for the clean energy transition, but it is also itself a sector that is particularly challenging to decarbonise. Consequently, the mining sector faces increasing pressure to decarbonise while simultaneously expanding to meet growing demand for metals and minerals.

Small modular reactors (SMRs) have emerged as a promising technology to support the decarbonisation of the mining sector. SMRs, including micro-SMRs, offer the potential to provide reliable, low-carbon heat and electricity for mining operations. This report on SMRs for mining is part of an NEA series of case studies to assess the opportunities and challenges for SMRs across industrial applications. This case study on SMRs for mining includes a qualitative assessment of the broad range of energy demands for electricity, heat and liquid fuels in mining, informed by interviews, surveys and broader engagement with stakeholders from mining value chains.

The analysis in this case study reveals an opportunity for small, off-grid mines that currently rely on diesel or heavy fuel oil for their energy demands and typically target high-value commodities. This report presents the cost of diesel consumption in these remote regions and suggests a possible role for micro-SMRs to be competitive with diesel generation at off-grid mines. A conservative global assessment of the existing and future potential market for micro-SMRs in these small off-grid mines is also included. Critical minerals such as rare earth elements, niobium, lithium, cobalt and copper were found to be commonly located in remote areas, suggesting the importance of off-grid mining to support a secure supply chain in support of the clean energy transition.

As policymakers and mining sector stakeholders work to understand the potential role of SMRs to support the decarbonisation of the mining sector, this report will serve as a resource to understand the drivers, characteristics and timelines for these technologies as they come to market.

Acknowledgements

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List of abbreviations and acronyms

CNL	Canadian Nuclear Laboratories
ESG	Environmental, social, and governance
GHG	Greenhouse gas
GWe	Gigawatts of electrical energy
GWth	Gigawatts of thermal energy
HFO	Heavy fuel oil
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INL	Idaho National Laboratory (United States)
LCOE	Levelised cost of electricity
MIT	Massachusetts Institute of Technology
MWe	Megawatts of electrical energy
MWth	Megawatts of thermal energy
NEA	Nuclear Energy Agency
SMIA	SMR Advisors for Industrial Applications
SMRs	Small modular reactors

Executive summary

Mining is essential to the global economy and in developing and producing the material needed for the clean energy transition. It is also a strategic sector for countries to secure domestic supply chain capabilities. The mining sector now faces broad pressure to decarbonise and simultaneously meet demand for increased production.

Environmental, social, and governance (ESG) frameworks for the improved sustainability of the mining sector are driving companies to explore innovation across the mining value chain. ESG policies frequently include targets to reduce total CO_2 equivalent emissions as well as the carbon intensity of mining activities. The world's largest publicly traded mining companies, with a combined market capitalisation exceeding USD 1 trillion, have committed to emissions reductions across their operations by or before 2050. These mining companies also operate within countries that have separate standalone commitments to achieve net zero emissions across all operations, which includes industrial processes such as mining.

The mining sector is among a growing group of hard-to-abate industries that are exploring small modular reactors (SMRs) among a range of clean energy technologies to support emission reduction targets in alignment with global net zero targets by 2050. This case study focused on mining is part of a series of reports that seek to inform policymakers about the drivers, detailed characteristics and timelines for SMRs to support the decarbonisation within these hard-to-abate sectors.

This report presents the results of a new NEA analysis that is founded on qualitative and quantitative sources of information and data. Extensive engagement with mining sector stakeholders - through surveys, in-depth interviews, and consultation with expert advisors from across the global mining sector – provided essential input about the business, technical, and operational requirements of the mining sector, and helped inform an understanding of the opportunity for SMRs to support mine-site decarbonisation. Quantitative analysis based on multiple global mining datasets complements the qualitative information collected directly from mining sector stakeholders and underpins the NEA's conclusions about the size and geographic distribution of the potential market for SMRs to provide heat and electricity to the mining sector.

This study explores the opportunities and challenges for SMRs, including micro-SMRs, to be an innovative and economically viable solution to power mines and help the global mining sector achieve ESG targets and emission reduction targets.

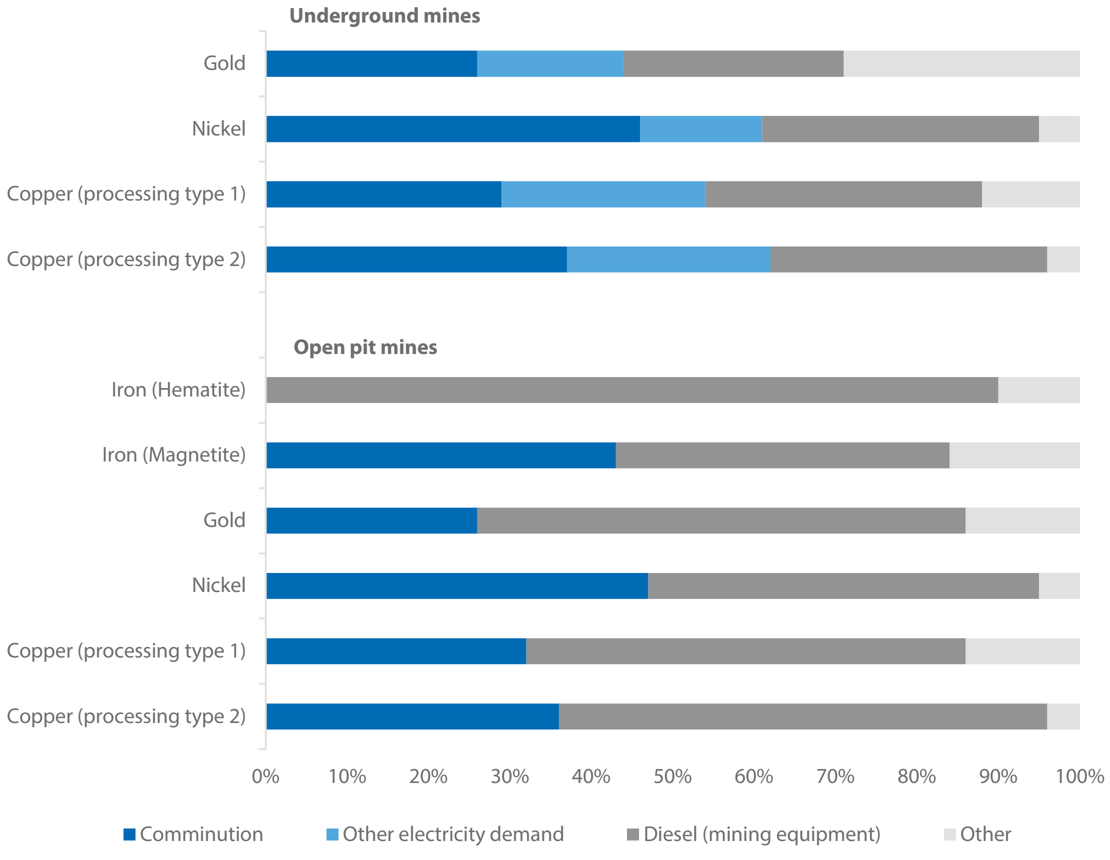
Energy demand for electricity, heat and liquid fuels in the mining sector is complicated and depends on the commodity of interest, the mining technique and other region-specific factors. Some mining operations require hundreds of megawatts of reliable power to satisfy electricity and thermal energy needs associated with primary mining activities, and mineral processing. This study includes a qualitative assessment and summary of end-user perspectives on the possible application of SMRs in the mining sector to support large power demands across the mining value chain, with a focus on primary mining activities.

For some mine types, electricity and thermal energy demands compose the majority of energy requirements, such as some solution mining techniques. For others, including more typical open-pit mines, up to 90% of energy demand can be associated with the consumption of liquid fossil fuels to power mining equipment or haulage vehicles. Energy availability is also considered critical for safety and successful operations at many mine sites, including for underground mines where electricity-powered ventilation ensures the safety of the workers and the proper functioning of equipment.

Figure ES1 below provides an indication of the variety of power demands at mine sites depending on commodity and type. In general, the primary demand for electricity at mine sites is often a common processing technique called comminution, which is the process of breaking rock into smaller components. Comminution accounts for approximately half of the energy consumption in the mining sector, where an electric motor on the order of 10-30 MWe may be required for a single processing unit.

The overall power demand also varies significantly depending on a variety of factors. A single mine site may require more than 80-400 MWe of electricity for grid-connected mines, while off-grid mines typically require less power ranging from 2 to 50 MWe but also up to 150 MWe in some cases.

Figure ES1: **Diversity of energy demand in metal mining as a function of commodity, processing, and local geology**



Note: Processing type 1 refers to leach processing with solvent extraction and electrowinning, while processing type 2 refers to the use of flotation plants with copper concentrators.

Source: Adapted from Allen (2021).

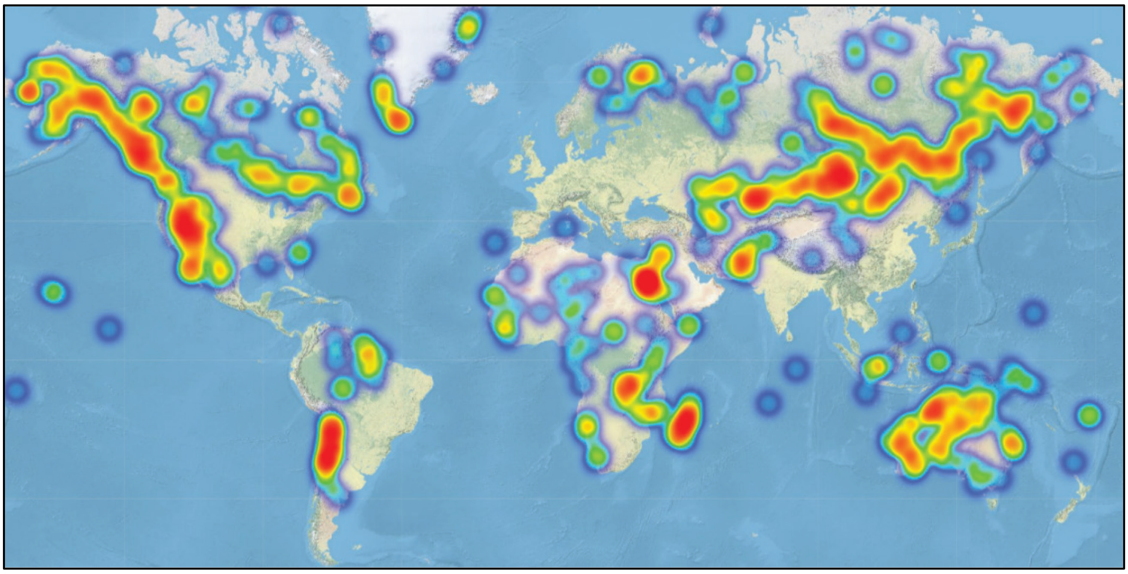
Stakeholders in the mining sector identified a range of barriers to SMR adoption at mine sites which include uncertainty around cost, regulatory and permitting aspects, and public perception as the primary areas of concern. End users noted that in general they do not wish to operate an SMR themselves, and instead prefer to buy the heat and electricity required to enable their operations.

There are also small off-grid mines that generate their required energy from diesel or heavy fuel oil and are typically characterised by elevated and volatile relative operating costs. This study approximates the number of existing off-grid mines and mineral deposits that are in remote locations, which is presented in Figure ES2. This distribution of off-grid mines and mineral deposits in remote areas is used to qualitatively assess a market size for micro-SMRs to support decarbonisation of small off-grid mines. These off-grid mines were found to have a median installed thermal generating capacity of 16 MWe and a characteristic operational lifetime of 15 to 20 years.

Figure ES2: **Existing mines and mineral deposits determined to be more than 20 kilometres from an electricity grid**

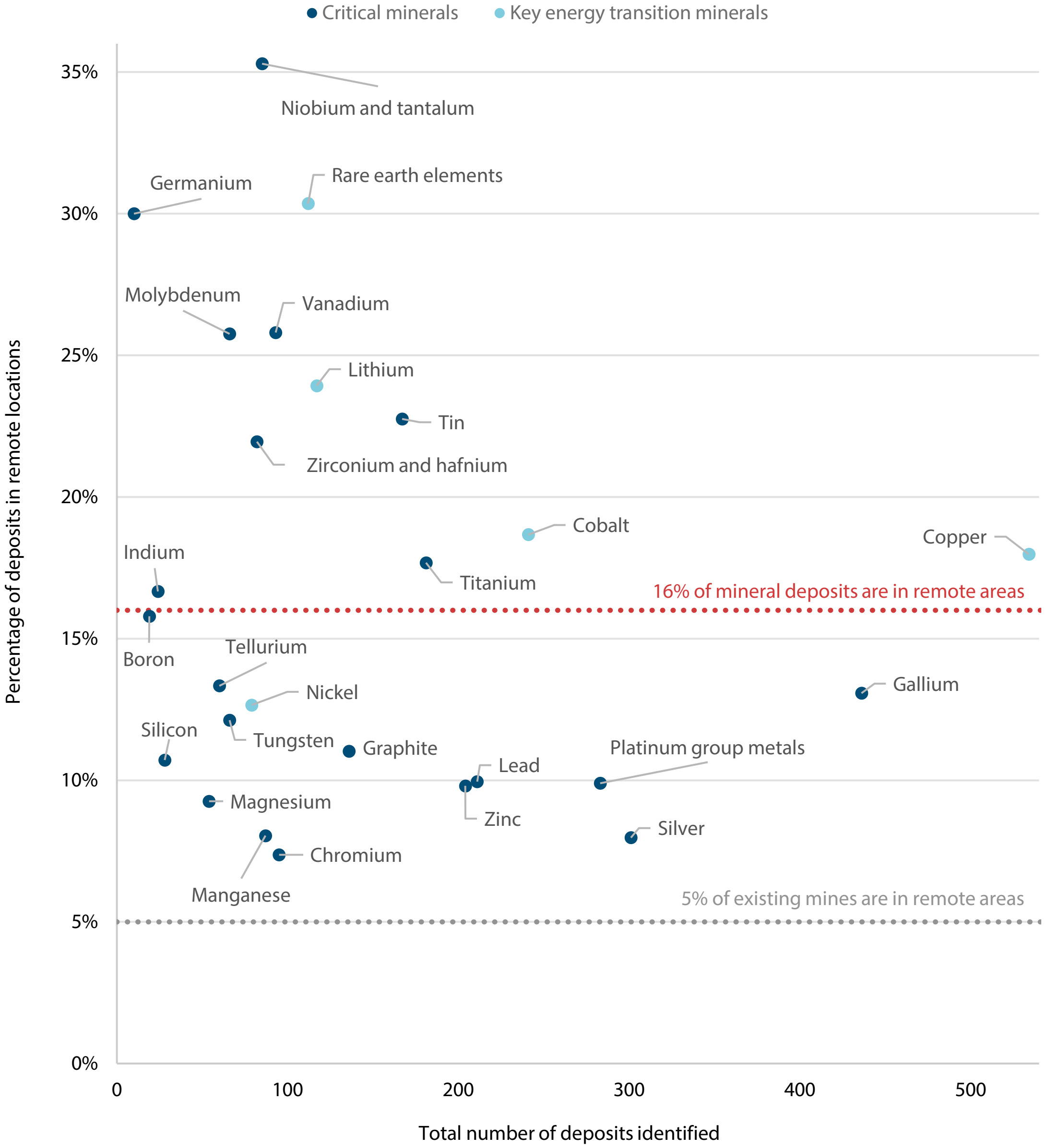
a) Existing mines more than 20 kilometres from an electricity grid

b) Remote mineral deposits more than 20 kilometres from an electricity grid



Predicted costs for micro-SMRs were found to be competitive with diesel generation for off-grid mining applications in remote regions, with estimated values suggesting a 31% cost advantage on a levelised cost of electricity (LCOE) basis. Proximity to the electricity grid was determined to be a key driver in the feasibility of a mining project. In 2024 off-grid mines represented only 5% of global mining activity. In contrast, 15.8% of mineral deposits identified through the US Geological Survey were determined to be in remote areas which have the potential to develop into mines in the future.

Figure ES3: **The determined accessibility of global critical mineral deposits including key energy transition minerals**



Note: Key energy transition minerals have been identified by the International Energy Agency in the 2023 critical mineral market review. They are rare earth elements, lithium, cobalt, copper, and nickel.

Finally, this case study includes an analysis on the availability of critical minerals, which are integral to the functionality of renewable energy systems, energy storage and electric vehicles. While critical minerals are found in low concentrations alongside other minerals, mineral deposits with high concentrations of these commodities are often found in remote areas in higher proportions when compared to primary metals and minerals.

NEA analysis has identified that the five key energy transition minerals identified in the International Energy Agency's Critical Minerals Data Explorer are more commonly found in remote areas, including 30% of rare earth element mineral deposits, 24% of lithium deposits, 19% of cobalt deposits, 18% of copper deposits, and 13% of nickel deposits, as illustrated in Figure ES3.

As the demand for clean energy continues to grow, the importance of ensuring reliable and diversified domestic supply chains for critical minerals will continue to grow. Meeting the demand for these critical minerals and ensuring a secure supply chain will necessitate exploration and mining in remote areas disconnected from current grid systems. Harnessing resources from remote areas will become imperative, necessitating innovative solutions for power generation in off-grid locations currently reliant primarily on diesel fuel.

There is strong potential for SMRs to play a crucial role in the mining sector, with an immediate opportunity to support off-grid mining operations. These compact and scalable nuclear power systems offer a reliable and efficient energy source, addressing unique challenges in the mining sector. Off-grid mining operations often have no viable access to traditional grid infrastructure, making them reliant on costly and environmentally unsustainable diesel generators. SMRs, with their compact size and modular design, can provide a stable and continuous power supply, reducing reliance on fossil fuels and potentially reducing operational costs.

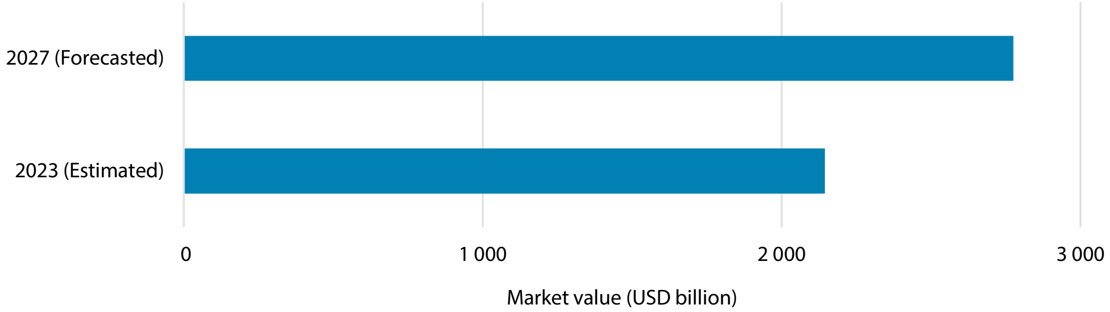
Chapter 1. Introduction to the potential role of SMRs for mining

The clean energy transition will require a significant amount of new material to manufacture wind turbines, solar panels, electric vehicles, energy storage technologies, and other clean energy technologies (IEA, 2021). Mining is a critical component of this transition and is a topic of geopolitical interest as countries work to prioritise domestic supply chain security. Small modular reactors (SMRs) could play a crucial role in mining operations for these minerals by offering compact and scalable power systems for both large scale mining and processing applications and for remote mines without access to traditional power infrastructure. SMRs would provide a stable and continuous power supply as an alternative to diesel generation, reducing reliance on fossil fuels and offering predictable and reduced operational costs.

The mining sector's energy and environmental challenges

Globally, the mining market accounts for more than USD 2 trillion in economic activity and is currently growing at a compound annual rate of at least 6% (RM, 2023). This rate of growth in the mining sector is expected to accelerate further in response to demand for raw materials to support the clean energy transition.

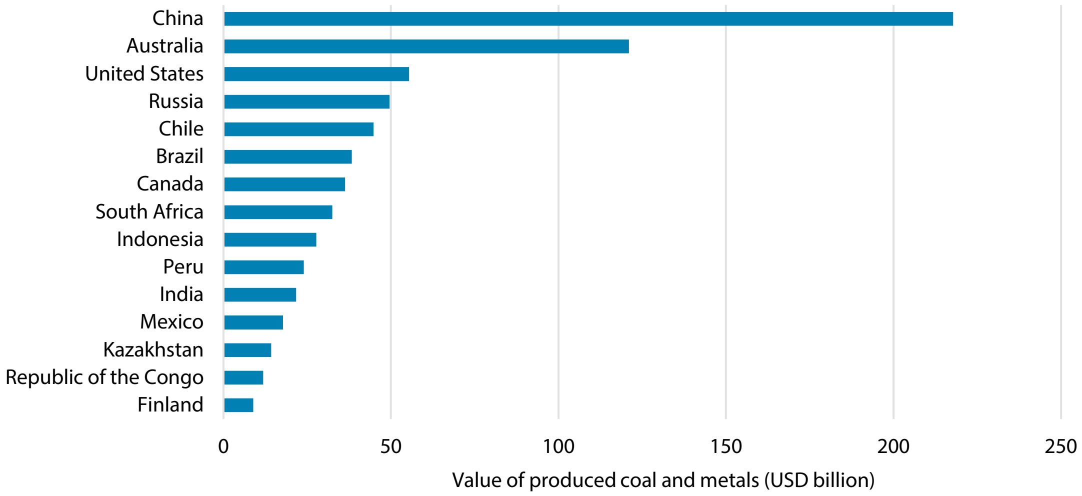
Figure 1.1: **Value of the global mining market and forecasted near-term growth**



Source: RM (2023).

Resource extraction in general, and metal mining in particular, significantly contributes to the economy of countries on every continent. As of 2022, the People's Republic of China (hereafter "China") is the country with the highest production value of mining activity globally, followed by Australia, the United States, Russia, Chile, Brazil, Canada, South Africa, Indonesia and Peru (ICMM, 2022). China has also become a dominant supplier of critical minerals such as rare earth elements, accounting for more than 80% of the global supply (Deloitte, 2021). In recent years, restrictions on the export of these minerals from China has created price volatility and availability challenges which have led countries to re-evaluate domestic critical mineral production (IEA, 2021; IEA, 2023b).

Figure 1.2: **Countries with the highest value generated from coal and metallic mining production activities in 2020**



Source: ICMM (2022).

The global percentage of CO_2 equivalent greenhouse gas (GHG) emissions associated with the mining industry ranges between 2-3% (Legge et al., 2021). Approximately one-third of these emissions are related to electricity production, and almost half are attributed to liquid fuel consumption in mining equipment or vehicles. In contrast to minerals and metals mining, the associated downstream processing activities represent a much larger share of global GHG emissions at approximately 7%. Nearly 90% of the emissions related to the processing of metals are associated with life cycle emissions of ferrous materials through iron and steel production. In particular, the refining and smelting process involves the use of fossil fuels to achieve temperatures exceeding 1 000°C (Ritchie et al., 2020; Hatch, 2016; Cox et al., 2022). This study focuses on primary mining activities, but also includes broad considerations for SMRs in downstream processing activities. While the emissions of metal mining are relatively small compared to these other hard-to-abate industrial processes, emissions reductions in the mining sector are essential as mining is a necessary precursor to global decarbonisation.

Historically, negative environmental aspects of mining extend well beyond carbon emissions. Mining base metals like gold, copper, and nickel can result in mine waste that, employing traditional mining practices, has the potential to leach acidity into the surrounding environment and water tables that threaten ecological harm. The disposal of mining waste, including hazardous tailings, can also lead to soil and water contamination (OECD, 2019).

The mining sector is also working to increase production to satisfy infrastructure demand requirements for the global clean energy transition. The World Bank, for example, projects a 6x growth by 2050 in mineral and metal production broadly (World Bank, 2020).

The mining sector is therefore undergoing a significant transformation to respond to a need to reduce industrial sector GHG emissions, to improve the environmental performance of mining operations, and to increase the production of metals mining to satisfy demand projections for material requirements. This transition is driving innovation in energy technologies. In recent years, mining companies have taken significant steps to increase the portion of electricity generation from renewable energy, invest in and deploy energy storage and hydrogen production technologies, and adopt more efficient mining practices to reduce the energy intensity of mineral production. These initiatives demonstrate the industry's capability and willingness to transition towards low-carbon energy sources and suggest uncertainty in long-term price predictability of energy at a mine site.

The energy demand at mine sites varies significantly based on location, size of operations, and the type of minerals being extracted. Each mining operation carries a distinct set of requirements and unique solutions. The unique energy requirements of the mining sector is explored in greater depth in Chapter 2.

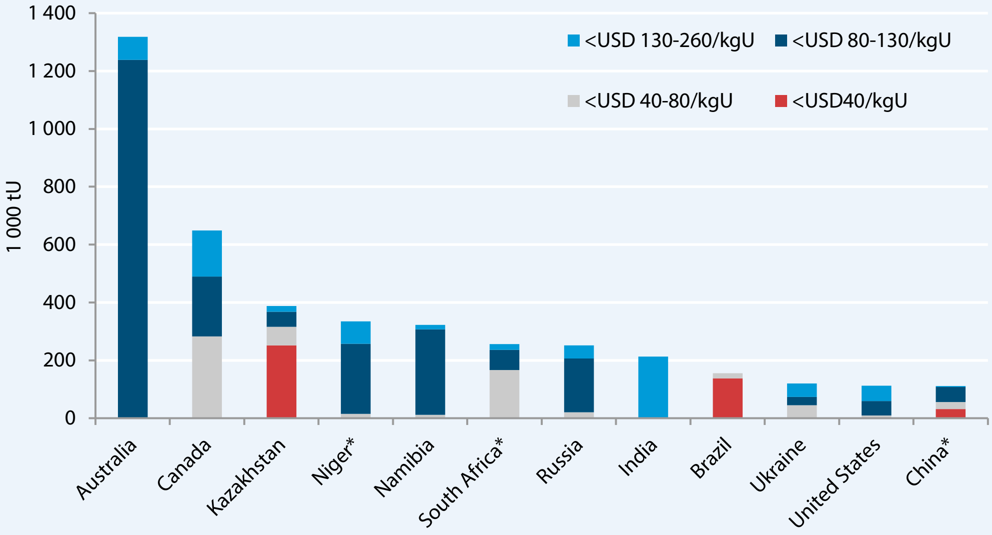
As a source of low-carbon heat and electricity, innovation in nuclear energy technologies offers a potential solution to help the mining sector increase production while minimising environmental impacts. The nuclear and mining sectors share some similarities regarding community stakeholders, sizeable operational scale, risk profiles, and their pivotal role in stimulating job creation and economic growth in rural areas. Jobs in these sectors range from specialised roles in engineering and technical operations to various support services, thereby diversifying the local job market (NEA, 2023a). Moreover, the presence of these industries can often spur infrastructural development, such as transportation and communication networks, further supporting localised communities. Uranium mining also serves as a strong linkage between the two industries.

Box 1.1. **Uranium mining and SMRs**

Uranium mining is unique, given additional regulatory scrutiny related to handling radioactive material. This impacts the transportation of material on-site, environmental protection practices, worker safety requirements including the ventilation requirements for underground mines, the presence of additional qualified personnel with expertise in radiation, and the volume of material that can be produced over a period.

The global distribution of recoverable uranium resources is concentrated in a small number of countries. Different mining methods are used depending on the jurisdiction, geology, and available energy options, which impact the expected costs of production as seen in Figure 1.3. These production costs further concentrate the global development of uranium mines. In contrast to the available uranium resources indicated in Figure 1.3, as of 2020, Kazakhstan is the largest producer of uranium, representing 41% of supply, followed by Australia, Namibia, Canada, and Uzbekistan, respectively (NEA, 2023b).

Figure 1.3: **Distribution of reasonable assured recoverable conventional uranium resources among select countries with a significant share of resources**



* NEA estimate or partial estimate.

Source: NEA, 2023b.

Compared to mining broadly, uranium mines typically require higher proportions of electricity compared to other energy requirements such as thermal energy or liquid fuel use. This is partially because the high proportion of uranium mines that are either in situ leach mines or underground mines, which typically require a higher proportion of electricity compared to open-pit mining due to the increased use of pumps, ventilation, and environmental control, all of which are subject to oversight by the nuclear regulatory body. To ensure the safety of mining employees from radioactive material, ventilation requirements are increased which also drives an increase in the required electricity to ensure air quality is sufficient.

At Cameco's Cigar Lake uranium mine in Canada, there is a significant electricity demand to freeze the ground prior to bore mining to ensure ground stability and prevent water from entering the uranium ore body, which both pose a safety risk for the workers in the underground mine.

These additional operational requirements are familiar to the nuclear energy sector, as resources are required to protect workers and the public from radioactivity. This includes strict safety standards, engagement and compliance with nuclear regulators, and the management of radioactive waste.

As an upstream component of the supply chain for nuclear energy, the uranium mining sector and the nuclear energy sector are intrinsically linked. This may result in synergies when using nuclear energy to power uranium mines, especially as the demand for uranium mining is expected to be closely correlated to the demand for nuclear energy.

Both sectors demand a high level of technical expertise in nuclear science and engineering, particularly pertinent to the handling and processing of uranium. This shared knowledge base may enable uranium mining companies to upskill employees to adopt SMRs more readily. As uranium mining is included in the supply chain for most SMR designs under development, the sectors could also benefit from supply chain integration. This may help ensure a steady supply of raw materials for power generation, facilitating economic growth through job creation, skill development, and trade.

Finally, uranium is known to be abundant, and could theoretically be extracted from mineral processing of other commodities, or from ore tailings in a mine's waste stream (IAEA, 2023). By implementing SMRs at a mine site, there may be increased opportunities to engage nuclear regulators and explore the possibility of producing uranium as an additional commodity and value stream for a metal mine.

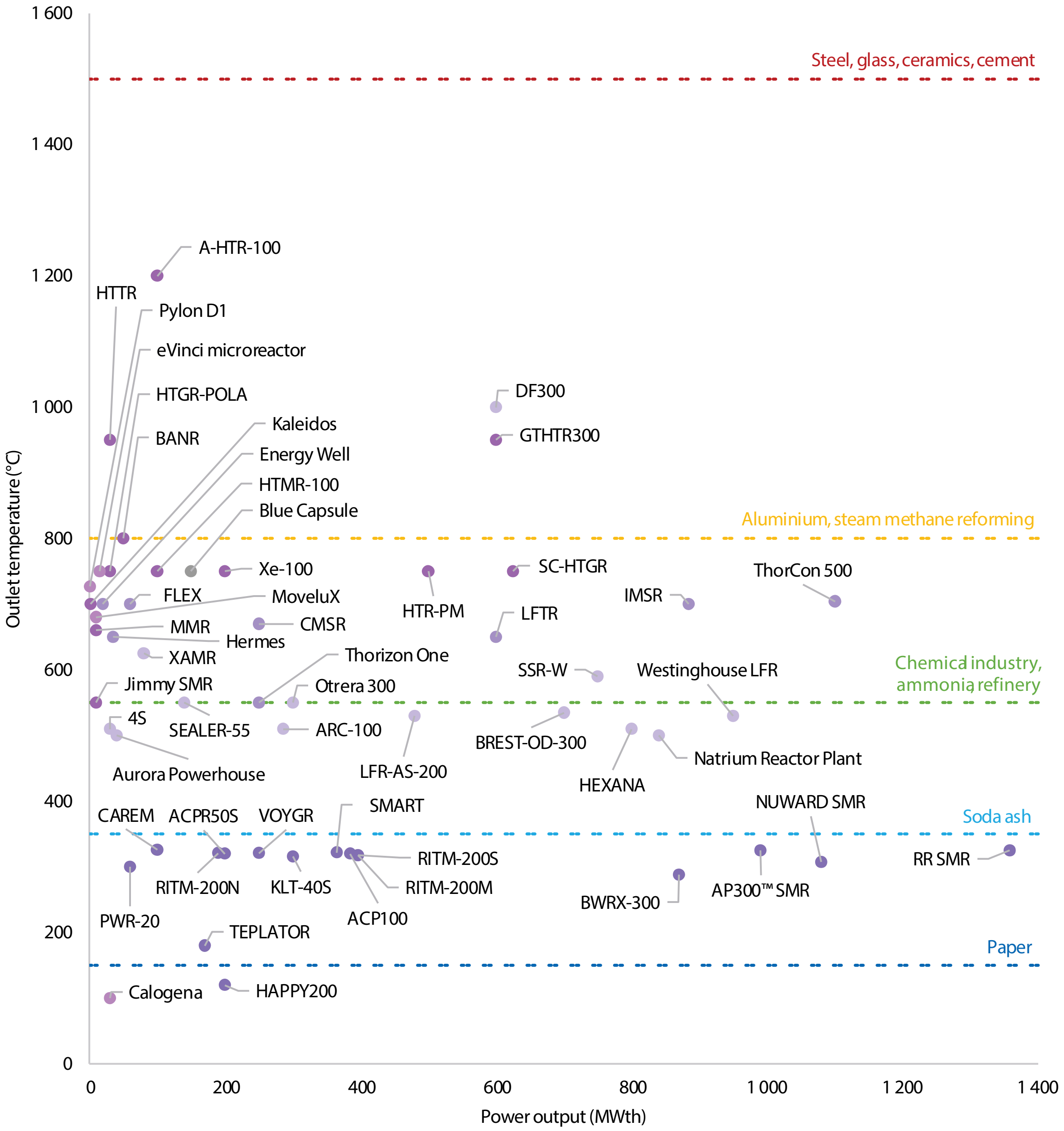
Small modular reactors

SMRs are a subset of nuclear reactor designs with a reduced power output and physical footprint compared to traditional nuclear reactors. Designed for modularity, SMRs are often characterised by the ability to be constructed using factories instead of building the nuclear reactor on-site. The electrical output of SMR designs can vary, with some providing up to 300 megawatts of electricity (MWe) or more for grid-connected reactors and others as low as 3 MWe or less for micro-SMRs. Some SMRs may offer additional features in terms of safety, operational simplicity, temperature of usable heat, and innovation in fuel.

Micro-SMRs refers to a broad classification of technologies but are expected to feature enhanced transportability, extended refuelling timelines, and be specifically designed for micro-grids or isolated industrial applications that demand a dedicated and reliable supply of heat or electricity.

There is significant activity globally to advance the commercialisation of SMR technologies for a range of application. Through the NEA SMR Dashboard initiative, the NEA is tracking progress on 63 SMRs for applications that extend beyond electricity production with technologies varying in both size and temperature, as illustrated in Figure 1.4 (NEA, 2024).

Figure 1.4: **Range of sizes and temperatures for heat applications**



Source: NEA, 2024.

The role of SMRs for the mining sector

There is evidence that SMRs may be uniquely well-suited to provide heat and electricity to mining operations, and there is particular support for micro-SMRs as a potential solution to specific applications in remote industrial settings. Specific SMR technologies that are being advanced to support the mining sector are explored in detail by both the International Atomic Energy Agency's (IAEA) *Advances in Small Modular Reactor Technology Developments: 2022 Edition* (IAEA, 2022) and the NEA's *Small Modular Reactor Dashboard: Second Edition* (NEA, 2024). Both publications identify clear progress of specific SMR vendors as a power solution for the mining sector, with several vendors advancing to demonstration and deployment.

Various efforts from different geographical regions and research institutions collectively underscore the potential benefits and applicability of SMRs in mining operations. Table 1.1 highlights specific activities that mining companies are undertaking worldwide to explore or advance projects to deploy SMRs at mine sites, including for mineral processing applications.

Table 1.1: **Public announcements of mining operations advancing or considering SMR deployment projects**

Mine site	Mine description	Project description	Size and timeline
Baimskaya Copper Mine, Cape Nagleynyn, Russia	Remote metallic mine at a brownfield site, with on-site processing	A licence to construct and deploy a series of RITM-200S marine-based SMRs is underway in Russia to supply heat and power to the Baimskaya copper mine and processing facility in Cape Nagleynyn.	300 MWe in total, with the first unit expected in 2027.
Seligdar Gold Mine, Yakutia, Russia	Remote metallic mine at a brownfield site	The project will deploy a RITM-200N land-based SMR to provide power to gold mining operations owned by Seligdar and the nearby towns in the region of Yakutia.	An off-take agreement was secured for up to 50 MWe, with deployment expected in 2028.
Sovinoye Gold Deposit, Chukotka, Russia	Remote metallic mineral deposit for a greenfield mine site	In the region of Chukotka in Russia, the SHELF-M micro-SMR is being considered to supply power to the Sovinoye gold deposit and nearby settlements.	10 MWe for deployment by 2030.
KGHM Copper Mine, Poland	Grid-connected metallic mine at a brownfield site, with on-site processing	KGHM Polska Miedź SA is working with NuScale Power on a project to deploy SMRs to produce electricity for their copper and silver operations. to power KGHM's operations by 2029.	More than 400 MWe with operations beginning in 2029.
Tata Chemicals Soda Ash, Green River, Wyoming, United States	Grid-connected non-metallic mine at a brownfield site, with on-site processing	Tata Chemicals Soda Ash Partners has signed an agreement with BWXT Advanced Technologies to assess the viability of deploying BANR micro-SMRs to supplement existing power at their soda ash mining and processing facility.	A single BANR SMR produces 50 MWth, and the project aims to support the company's goal to reduce emissions by 30% by 2030.

In Russia, projects are already underway to deploy SMRs at remote mine sites. The RITM-200 pressurised water reactor design that is already licensed and in operation on the icebreaker ships Arktika, Sibir, and Ural has been adapted to produce power for future mining operations and meet the local needs of remote regions in Russia. A series of floating power units using the RITM-200 technology will be used to provide 300 MWe of power to the Baimskaya copper mine and processing facility located in north-eastern Russia, and a land-based version of the same design will power the existing Seligdar Gold Mine in a remote region of Yakutia (NEA, 2024). The SHELF-M micro-SMR is also being considered to provide 10 MWe of power to the Sovinoye gold deposit and nearby communities in the Chukotka region (Rosatom, 2023).

The KGHM mining company in Poland is also advancing a project to deploy SMRs to provide more than 400 MWe of electricity to power KGHM's copper and silver mining operations by 2029. KGHM is exploring multiple light-water SMR technologies for this project and has signed an agreement for the SMR technology developer NuScale to support their application to Poland's National Atomic Energy Agency. In July 2023, the Ministry of Climate and Environment approved a decision in principle for KGHM to proceed with deploying SMRs at their mine site as early as 2029 (KGHM, 2023)

North America also has a significant interest in deploying SMRs to power mining operations. In addition to the SMR demonstration projects moving forward, there is a range of studies evaluating the suitability and feasibility of SMRs for mining operations in North America (Canadian SMR Roadmap, 2018; Wojtaszek, 2017; Bayomy et al., 2023; Macdonald & Parsons, 2021; Hatch, 2016).

In Canada, as part of a joint venture between Ontario Power Generation and the SMR technology developer Ultra Safe Nuclear Corporation, an SMR demonstration project is moving forward at Chalk River Laboratories in Ontario, intended for various applications, including mining. In the Canadian province of Saskatchewan, the Saskatchewan Research Council is working with Westinghouse to explore the deployment of the eVinci micro-SMR with potential applications in the mining sector. The Australian mining company BHP has implied that they may consider SMRs among a range of clean energy technologies to provide power to the Jansen potash mine in Saskatchewan (Cranston, 2023), which could utilise thermal energy from an SMR to support potash drying activities.

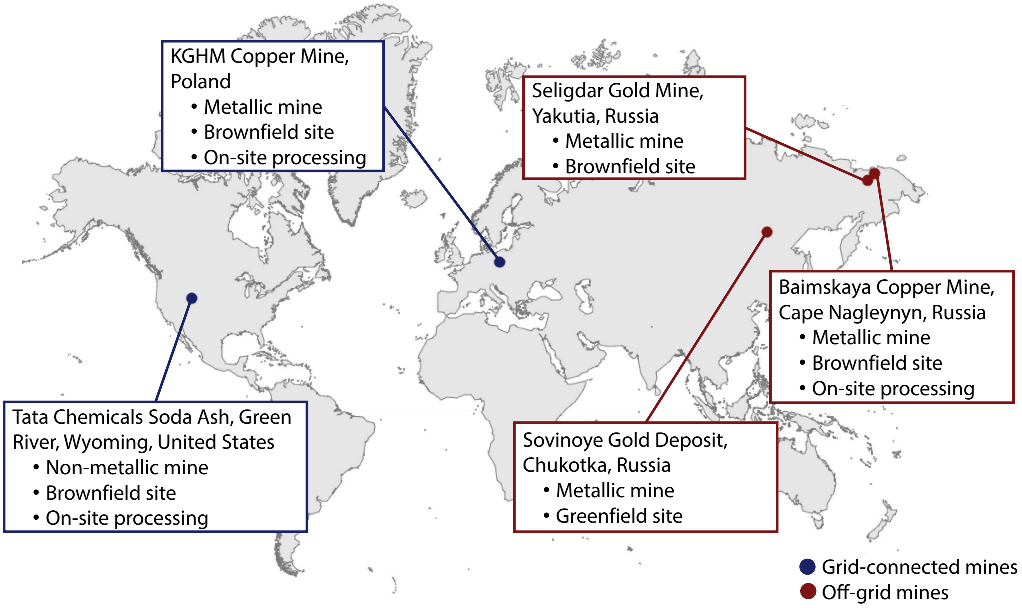
In the United States, demonstration projects are moving forward in multiple jurisdictions. Tata Chemicals Soda Ash Partners is working to evaluate the role of SMRs for their operations in Wyoming and has signed a co-operation agreement with BWXT Advanced Technologies to assess the viability of deploying BANR micro-SMRs to supplement existing power at their soda ash mining and processing facility and to support the company's goal to reduce emissions by 30% by 2030. Several studies and engagement activities also focus on the potential deployment of micro-SMRs in Alaska to provide heat and power to remote mining or off-grid communities (Tata Chemicals, 2023).

A 2023 study in the United States also suggests that mine sites are generally well-suited to host SMRs. The study identifies seven potential locations in Southwest Virginia for SMRs, including a site at a former limestone mine (Dominion Engineering, 2023). The study used the Siting Tool for Advanced Nuclear Development, which aggregates data from multiple governmental sources to evaluate the suitability of the sites. Mining operations typically have well-characterised seismology and geologic data, which are common requirements to secure environmental approvals for new nuclear energy installations.

SMRs benefit from significant momentum and interest in achieving the environmental goals of mining operations. The enabling role of SMRs is being demonstrated to support energy challenges across a range of mine types, including metallic, non-metallic, and energy resource mining. The distribution of mining operations that are exploring SMRs for both metallic and non-metallic mining is illustrated in Figure 1.5. Energy resource mining is beyond the scope of this study except for uranium mining, which is discussed qualitatively in Chapter 2. There is also notable interest in using SMRs for energy resource mining, including supplying thermal energy to reduce emissions in the oil and gas sectors. These examples demonstrate two distinct opportunities for SMRs in the mining sector. The first is the need for hundreds of MWe of reliable power from larger SMRs for both metallic and non-metallic mining applications where on-site processing is typical. Power at these mines is typically supplied by electricity grid connection or dedicated thermal generation with backup diesel, heavy fuel oil (HFO), or coal generation to ensure peak demand and reliability. Mining operations of this type are more popular and focus on an extensive range of metallic commodities, such as copper and iron-bearing products, and non-metallic commodities, such as potash and soda ash.

The second opportunity for SMRs in the mining sector is using micro-SMRs for remote metallic mining at both brownfield off-grid mine sites and remote mineral deposits where a new mine would be built. A representative off-grid mine has a primary electricity requirement of between 5 MWe and 30 MWe (Wojtaszek, 2017), with waste heat being used for localised district heating or other low-grade applications. Mines of this type typically use diesel, HFO, or natural gas as a primary energy source and target high-value commodities such as gold, diamonds, and critical minerals. The role of SMRs in the mining sector is of particular interest due to the costs associated with operating in remote regions.

Figure 1.5: **Distribution of mining operations that are advancing or considering SMRs for their operations**



Off-grid mining and SMRs

The competitiveness of SMRs rests on the costs associated with building and deploying the technology and the policy frameworks in place. It also depends on the alternative energy options within a given market. Costs are higher in remote locations, and the energy options are more limited for end users.

Remote mining faces particular challenges linked to transportation requirements and lack of infrastructure. A small percentage of mines are isolated, off-grid, and self-generate energy to sustain mining operations, estimated to represent approximately 5% of global mining activity (Hatch, 2016). Remote and off-grid mines typically rely on fossil fuels, with a particular reliance on diesel and HFO – both of which have faced price increases and volatility in recent years. Off-grid mines are more expensive to operate than grid-connected mines due to material, personnel, and equipment transportation costs.

The reliance on diesel, especially for off-grid mining, poses environmental, logistical, and cost-related challenges, highlighting the need for more sustainable and efficient energy alternatives. Countries and companies with off-grid or self-generating mining operations are exploring opportunities to reduce the environmental impact of off-grid mining while increasing or maintaining production quantities to satisfy market demand for high-value commodities. Low-carbon energy solutions for remote mining, such as SMRs, will be essential to support the clean energy transition. As a result, there is a significant body of research exploring off-grid markets for SMRs (Wojtaszek, 2017; Macdonald & Parsons, 2021; Bayomy, 2023; Shropshire et al., 2021; Aumeier et al., 2023; Caron, 2021) as well as modelling of off-grid mining markets or other isolated grids around the world (Carvalho et al., 2014; Balaji and Gurgenci, 2019; AECOM, 2014; Votteler and Brent, 2016).

There are many off-grid mines that require power generation capacity under 30 MWe, making micro-SMRs an attractive technology. Chapter 3 of this report explores the characteristics of these smaller off-grid mining operations in greater detail. In contrast there are large, established mining operations that process minerals on-site which typically require substantially more power than off-grid mines. These mines could potentially adopt larger SMRs. In both cases, demand for power will grow as mines adopt electrification and other alternative processes to decarbonise their operations.

Micro-SMRs are being commercially developed for various applications, including for deployment at small off-grid mines. Micro-SMRs represent a significant portion of the SMRs being developed worldwide. Of the SMRs included in the *NEA Small Modular Reactor Dashboard* assessments in 2024, 12 were identified as micro-SMRs – the majority of which are exploring off-grid markets in remote regions.

The costs of building and operating SMRs at a mine site remain uncertain. This is especially true for micro-SMRs, as these commercial technologies have not yet been demonstrated or deployed. Some micro-SMR demonstration projects, including designs that are targeting mining applications, are expected to come online in the mid- to late-2020s.

Objectives, methodology and structure of the report

In light of the increasing interest in SMR technology and the need to increase mining productivity to support the global clean energy transition, this report aims to inform policymakers about the main drivers, detailed characteristics, and timelines for SMRs to power mining operations, with a quantitative focus on off-grid mining.

Chapter 2 provides a review of the energy requirements for the mining sector and the industry's efforts to improve ESG performance—including a consideration of how SMRs might play a role in the future. Direct engagement with stakeholders involved in the mining value chain was achieved through structured interviews and a distributed survey to inform this analysis and identify the potential gaps associated with deploying SMRs at mining operations. Additionally, a set of advisors was convened from industrial sectors in NEA member countries. This set of NEA SMR Advisors for Industrial Applications (SMIA) enabled the NEA to engage with prospective users exploring SMRs as an option to support industrial decarbonisation and consolidate demand-side perspectives. SMIA also provided expert input and strategic review of this study. End users commented on the specific energy and technical requirements of their organisation's mine sites and shared their views on barriers and enabling conditions for SMRs to support the decarbonisation of the metals sector. End users also commented on the range of energy options under consideration, and the diversity of applications throughout the metals sector.

This industrial case study also provides an overview of the potential market for SMRs at off-grid mines. A quantitative assessment of the potential accessible market for SMRs or micro-SMRs for off-grid mining applications is presented in Chapter 3. This market assessment evaluates the existing market for brownfield mining operations, which refers to off-grid mines currently operating or being constructed. Off-grid mines currently typically rely on diesel and HFO and represent an opportunity to replace existing generation capacity with SMRs through retrofit. The quantitative assessment also predicts a market opportunity for future greenfield mining operations that could be developed in remote areas using SMRs as an on-site energy option for electric and thermal energy generation. This includes an assessment of mineral deposits in remote areas and a detailed assessment of the relative abundance of specific critical minerals.

Notably, there is demand and interest for SMRs for mines that are connected to the grid but self-generate a portion of the energy demand to satisfy reliability requirements, and to satisfy thermal energy demand requirements. A detailed assessment of the demand from mines of this type is beyond the scope of this case study and will be discussed only qualitatively as part of an expanded market assessment. Additional factors expected to impact the overall market size for SMRs include incentivised demand linked to excess power in a remote area and additional on-site processing that may be adopted given newly available power at an economical cost.

Finally, this report serves as an initial source of information to support policymakers and end users in understanding the potential role of SMRs in the mining sector and the opportunity to power remote mines otherwise dependent on fossil fuels, like diesel, for power generation. The case study collates vital information and highlights drivers and enabling conditions for end users, governments, regulators, and other stakeholders to consider. The report provides relevant policy recommendations for policymakers to realise this market opportunity.

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Chapter 2. Energy requirements of the mining sector and efforts to improve ESG performance

Significant variation exists in the mining sector's technical, business, and operational needs, which depend on the commodity mined, the mining technique used, local considerations, and more. This chapter qualitatively introduces the range of requirements in the mining sector and characterises the key drivers that influence a mining company to adopt a particular solution to achieve their environmental and economic goals, including the potential opportunities and risks associated with deploying small modular reactors (SMRs) at mine sites. This chapter contains general requirements, while specific needs depend on individual characteristics of a particular mine.

The classification of mining activities is challenging, as the energy demands and technical requirements for mining processes cannot be well defined solely based on commodity. The range of commodities is presented in Figure 2.1, where mining activities are divided into metallic, non-metallic, and energy resource mining subcategories. Requirements at a mine site are also highly dependent on whether the mine is connected to an electricity grid, as well as the localised environment of the mining operation, which includes geological characteristics and the climate.

Figure 2.1: **Classification of commodity types that are mined**

Note: Classification developed by the NEA Secretariat to clarify the diversity of terminology used internationally.

In addition to commodity-specific requirements, a mine has specific requirements depending on the type of operations, primarily open-pit mining, underground mines, or in situ solution mining. For example, underground mines require ventilation infrastructure, solution mines require pumps to mobilise fluids, and open-pit mines have a higher relative requirement for on-surface transportation of material, such as haulage vehicles that consume diesel.

Finally, the type of processing adopted for the mining operation presents a third significant factor that impacts the characteristic requirements at a mine site. The type of processing depends on the minerology and grade of the material being mined, the environment and the availability of local infrastructure. Processing activities can be characterised by a combination of processes that reduce particle size through comminution, separating or isolating specific commodities, and drying.

Box 2.1. **A golden example: A tale of two mines**

The characteristics of a mining operation vary significantly depending on the commodity being mined, the environment, and the technologies deployed. Two gold mines in Canada present a helpful example of distinct operational requirements and energy needs in the same mining activity and federal jurisdiction.

Hope Bay is a fly-in and fly-out remote gold mine owned by TMAC Resources that has been operating commercially in the western territory of Nunavut since 2017. Hope Bay is primarily an underground mining operation with electricity requirements for ventilation and to ensure worker safety at the mine site. The ventilation system requires heating to provide an adequate work environment for the mine personnel and equipment. All power is generated on-site using eight 1.45-MW diesel generators supporting 2 000 t/day in gold production. All primary materials, including diesel fuel, mining equipment, food, and medical supplies, are transported to the mine site by ship when ice conditions allow for passage through the Arctic Ocean, typically between late July through September. There is also an airstrip for gravel-certified aircraft as well as air freight. Temperatures reach -30°C in the winter season, and the site experiences near continuous sunlight in the summer and darkness in the winter due to its latitude. Gold production is currently limited by the available mineral processing capacities on-site. TMAC Resources has plans to increase on-site processing to recover more gold through crushing, grinding, gravity concentration, flotation, and chemical leaching. The expanded processing activities will enable a mine expansion of an additional 4 000 t/day. Four new 7 MW diesel generators will be installed to support the expansions.

Detour gold mine in northern Ontario stands in sharp contrast, owned by Kirkland Lake Gold. The Detour gold mine is primarily an open-pit mine, with three separate open pits relying on a fleet of haulage vehicles powered by diesel fuel to transport material. The mine site and processing facility are connected to the electricity grid by a 180 km transmission line, providing the Detour Lake mining operation with more than 85 MWe of power. Backup generation is available on-site for emergency power to ensure the reliability and safety of operations. The processing facilities include grinding and leaching facilities, with ball mills consuming 15 MWe of electricity. The Detour mine is undergoing expansions to increase its output; however, these are not expected to increase energy consumption significantly. Instead, the focus is on achieving more efficient processing practices, leveraging the relatively low cost of electricity of USD 25/MWh. However, when this existing electricity contract expires in 2025, the cost of electricity is expected to increase to USD 74/MWh.

Even though these mines are both operating in the same country and producing gold, they have vastly different energy requirements as a result of their energy availability and mining methods. Hope Bay, an underground mine in a cold, remote area, relies primarily on diesel for power, emphasising the need for heating and ventilation. Detour mine, a large open-pit operation with grid access, utilises more electricity for ore extraction and material handling. The variations in energy types, availability, and the extent of processing required at each site highlight the diverse energy demands within the mining sector, even for mines extracting the same mineral in the same country.

Figure 2.2: **Hope Bay and Detour gold mine displayed on a map**

This comparison between open-pit and underground mining operations is also supported by the Mining Energy Consumption 2021 literature review, which explored more than 40 published studies that reference the range of energy requirements for mining activities. Underground gold mining requires an average energy consumption of 134 GJ/kg versus 372 GJ/kg for open-pit mining, a 177% increase in total energy consumption to produce a given quantity of gold from these two methods. In addition, the relative contribution of energy-intensive activities varies significantly between the two categories of gold mining operations. Underground gold mines typically require more electricity than their open-pit counterparts due to ventilation requirements. Conversely, open-pit gold mines consume much more energy through liquid fuel for haulage vehicles – 60% of total energy consumption compared to 27% for underground mines.

Source: Lawson et al., 2020; Leite et al., 2020; Allen, 2021.

Mining sector engagement results

The authors of this study extensively engaged with mining companies, mining associations, and additional organisations with expertise in the mining and mineral processing value chain, as summarised in Table 2.1. Mining sector stakeholders provided feedback on their organisation's specific energy and technical needs at mine sites and discussed potential obstacles for SMR adoption in the mining sector. They shared views on various energy alternatives being considered and insight on the variety of energy-intensive applications throughout the metals industry. This chapter includes a non-exhaustive inventory of these end-user requirements that have been identified through these engagement activities.

Table 2.1: **NEA engagement activities to inform and support this industrial case study for SMR markets on mining**

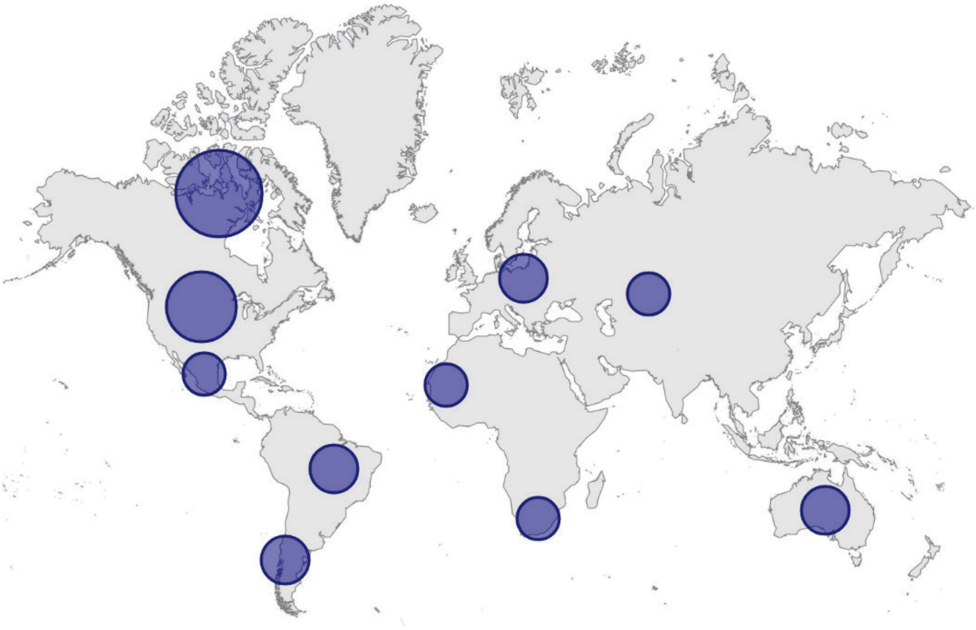
Engagement activity	Participation and timeline	Scope of activity
Virtual engagement sessions	4 sessions throughout summer 2023 reaching 106 individuals from 56 organisations.	Presentation targeting mining sector stakeholders on preliminary findings.
SMRs for mining workshop in Canada	Full day in-person workshop held in Toronto, Canada on 6 March 2024 with participation from 118 individuals from 70 organisations.	Presentation of findings and an interactive discussion among nuclear, mining, and financial sector stakeholders in Canada.
Mining sector end user survey	9 survey responses received throughout summer 2023.	Quantitative information to understand broad sector-wide considerations and the range of technical constraints within the mining sector.
Mining sector end user interviews	12 interviews conducted throughout 2023.	Qualitative discussion focused on detailed plant-level and organisational considerations.

Individual experts participated in structured interviews and a distributed survey to share quantitative data from their mining operations and perspectives regarding the energy transition in the global mining sector. Nine experts from the mining sector completed the survey, which included questions about their current energy sources, plans for decarbonisation, and the role that SMRs might play in energy strategies. The survey focused on quantitative aspects of a given mining operation to understand power requirements and processing activities, and gathered insights on the factors influencing energy decisions in the mining sector, like economic considerations, environmental impacts, and the suitability of energy assets.

In addition, 12 organisations participated in detailed interviews to respond to the survey questions and also to expand on additional considerations that impact the energy decisions in the mining sector. This included specific considerations for SMRs in a mining environment, challenges related to social licence and community relations, and detailed requirements for energy capacity at their sites. These discussions extended to alternative energy options being considered, and the process and criteria used in developing plans for energy infrastructure. Additionally, the interviews explored policy impacts that may facilitate the clean energy transition within the mining sector.

Combined, these stakeholders represent a diverse set of jurisdictions, commodities, and environments, which is represented in Figure 2.3. Mining sector engagement was also informed by the NEA SMR Advisors for Industrial Applications specific to Mining (SMIA-Mining), which was convened to understand the technical, business, and operational requirements of the mining sector were in order to adopt SMRs and other clean energy technologies. The SMIA-Mining stakeholders include organisations related to the mining and mineral processing value chain, including research institutions and utilities.

Figure 2.3: **Regional distribution of primary mining operations among mining companies that completed an interview or submitted input via a questionnaire in support of this study**



Note: The circles are placed at the geographic centroid of the associated host country. The size of the circles are related to the number of engagements that indicated primary mining operations in each country. The countries listed are Australia, Brazil, Canada, Chile, Kazakhstan, Mauritania, Mexico, Poland, South Africa, and the United States of America.

The majority of mining companies engaged through the survey and interview processes are already exploring the opportunity to deploy SMRs as a potential energy solution for their respective mining operations. For those that are considering SMRs, most are assessing the feasibility of adopting SMRs for their mining operations. A small number of those engaged are either in the early stages of exploring SMRs as a potential option or are actively in discussions with SMR vendors as a next step.

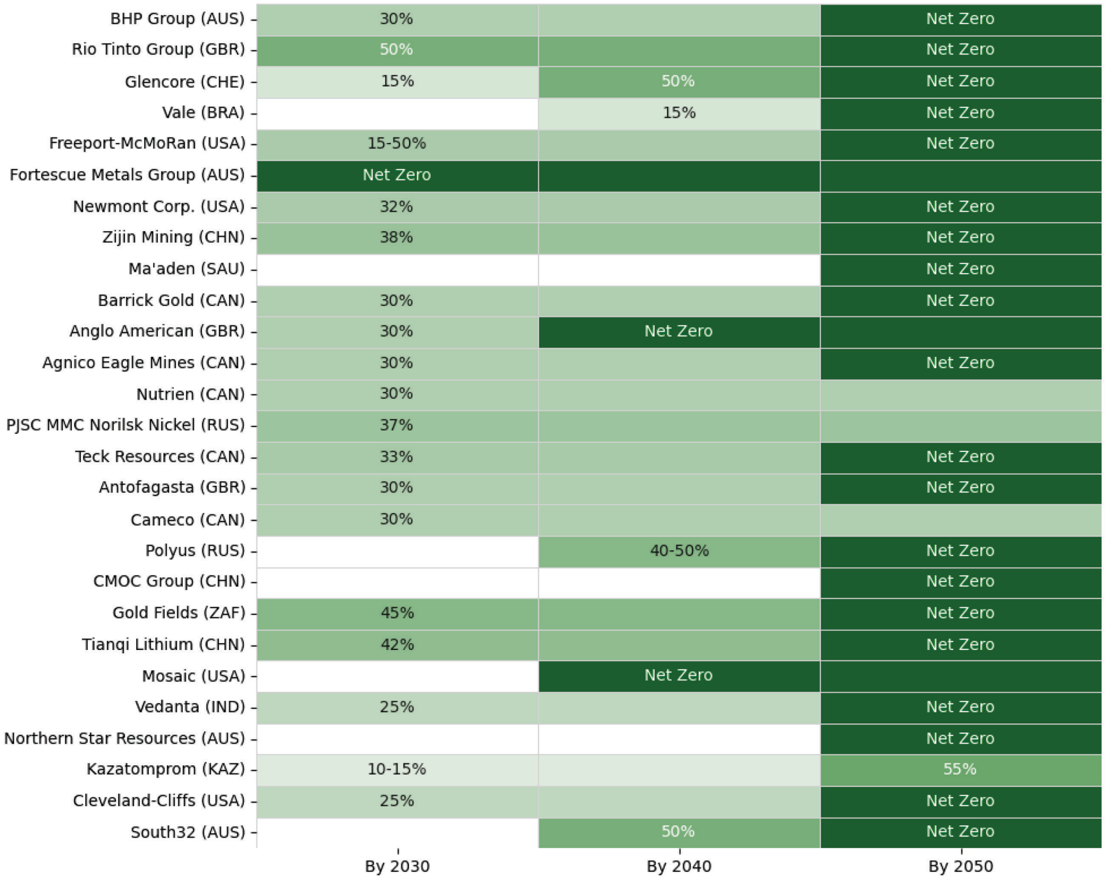
Among the mining sector stakeholders that participated in the interviews or surveys and are considering SMRs, the majority are interested in the role of SMRs to provide heat and electricity to large mining operations to offset reliance on on-site fossil generation or the grid-connected electricity supply. In contrast, approximately 40% of the engaged stakeholders are focused on the role of micro-SMRs for off-grid or remote mining applications.

Finally, stakeholders were engaged through a series of virtual engagement sessions in the summer of 2023 and an in-person workshop in Toronto, Canada in March 2024, which together reached 215 individuals from 105 different companies with an interest in the intersection of nuclear energy and the mining sector. These engagement sessions were used to share preliminary results from NEA analysis on the opportunity for SMRs in the mining sector. Additional stakeholders were reached through presentations at conferences where mining sector stakeholders as the primary audience, such as the Energy Transition and Emission Reduction for the Metal and Mining industry series of events, and the PDAC mining convention in Toronto, Canada in March 2024.

Environmental, social, and governance (ESG) performance

Governments and individual companies within OECD member countries are exploring opportunities to develop domestic supply chain capabilities, citing the human rights issues in the mineral supply chain, upstream supply chains concentrated in conflict-affected and high-risk jurisdictions, and domestic security of supply considerations (OECD, 2016).

Figure 2.4: **Emissions reduction targets reported by the world's largest publicly traded mining companies, sorted by market capitalisation as of December 2023**



	By 2030	By 2040	By 2050
BHP Group (AUS)	30%		Net Zero
Rio Tinto Group (GBR)	50%		Net Zero
Glencore (CHE)	15%	50%	Net Zero
Vale (BRA)		15%	Net Zero
Freeport-McMoRan (USA)	15-50%		Net Zero
Fortescue Metals Group (AUS)	Net Zero		
Newmont Corp. (USA)	32%		Net Zero
Zijin Mining (CHN)	38%		Net Zero
Ma'aden (SAU)			Net Zero
Barrick Gold (CAN)	30%		Net Zero
Anglo American (GBR)	30%	Net Zero	
Agnico Eagle Mines (CAN)	30%		Net Zero
Nutrien (CAN)	30%		
PJSC MMC Norilsk Nickel (RUS)	37%		
Teck Resources (CAN)	33%		Net Zero
Antofagasta (GBR)	30%		Net Zero
Cameco (CAN)	30%		
Polyus (RUS)		40-50%	Net Zero
CMOC Group (CHN)			Net Zero
Gold Fields (ZAF)	45%		Net Zero
Tianqi Lithium (CHN)	42%		Net Zero
Mosaic (USA)		Net Zero	
Vedanta (IND)	25%		Net Zero
Northern Star Resources (AUS)			Net Zero
Kazatomprom (KAZ)	10-15%		55%
Cleveland-Cliffs (USA)	25%		Net Zero
South32 (AUS)		50%	Net Zero

Note: Presented values are for illustration purposes only as they include generalisations across scope-specific emission targets. The baseline year for presented targets varies by company.

Source: Moors, 2022 and Mining.com, 2024, with emission target data supplemented by available public information.

To ensure the sustainability of the clean energy transition, the mining sector must adopt energy strategies that align with national or corporate emissions reduction targets and other ESG goals. The priorities identified by mining companies related to their energy decision drivers were primarily aligned with their respective ESG frameworks, suggesting alignment between a mining company's operations and expectations from investors and the public.

ESG policies within mining companies frequently include targets to reduce total emissions, as well as the carbon intensity of mining activities, both in the near term and to support net zero emissions by 2050. Public emissions reduction targets from mining companies are shown in Figure 2.4, which shows a subset among the 40 largest publicly traded mining companies globally that have committed to emissions reductions across their operations by or before 2050. The companies included in Figure 2.4 represent a combined market capitalisation of more than USD 1 trillion as of December 2023, demonstrating the significant global impact and economic opportunity of the clean energy transition within the mining sector. Clean energy is central to achieving these targets and to maintaining the competitiveness of companies and countries over the longer term in the global push to net zero emissions (Zarębski and Dominik, 2023).

While there is a goal to reduce or minimise the emissions associated with existing and future mining operations, remediation issues and environmental best practices in the mining sector also present policy priorities in NEA member countries. Innovation in processing may reduce the ecological footprint from mining operations, historically disincentivised due to the economics associated with heat and electricity production at mine sites.

The benefits of sound environmental practices also directly impact the future viability of a mining company. As a key contribution to upstream supply chains globally, producers of various materials may favour sourcing material from mining companies with sound environmental practices to satisfy ESG criteria of companies downstream in the supply chain. Some view this as a strategic opportunity to innovate in clean energy technologies to capture additional market size by becoming a trusted supplier relative to other competitors. Reducing greenhouse gas emissions and other environmental impacts associated with mineral development activities will also improve social acceptability in mining projects by creating supply chains that reflect current and future carbon pricing (NEA, 2023; IEA, 2023)

Concerning off-grid mining, mining sector end users with remote mining operations noted that the isolated operations of the mine pose the most significant risk to achieving ESG commitments. This is primarily due to the high costs associated with generating electricity in remote areas but also driven by the operational challenges of transporting supplies, personnel, specialised workers, food, and water to an isolated industrial site. In all cases, on-site generation is common, requiring fuel to be transported, typically in the form of diesel, propane, and heavy fuel oil.

Energy demand at mine sites

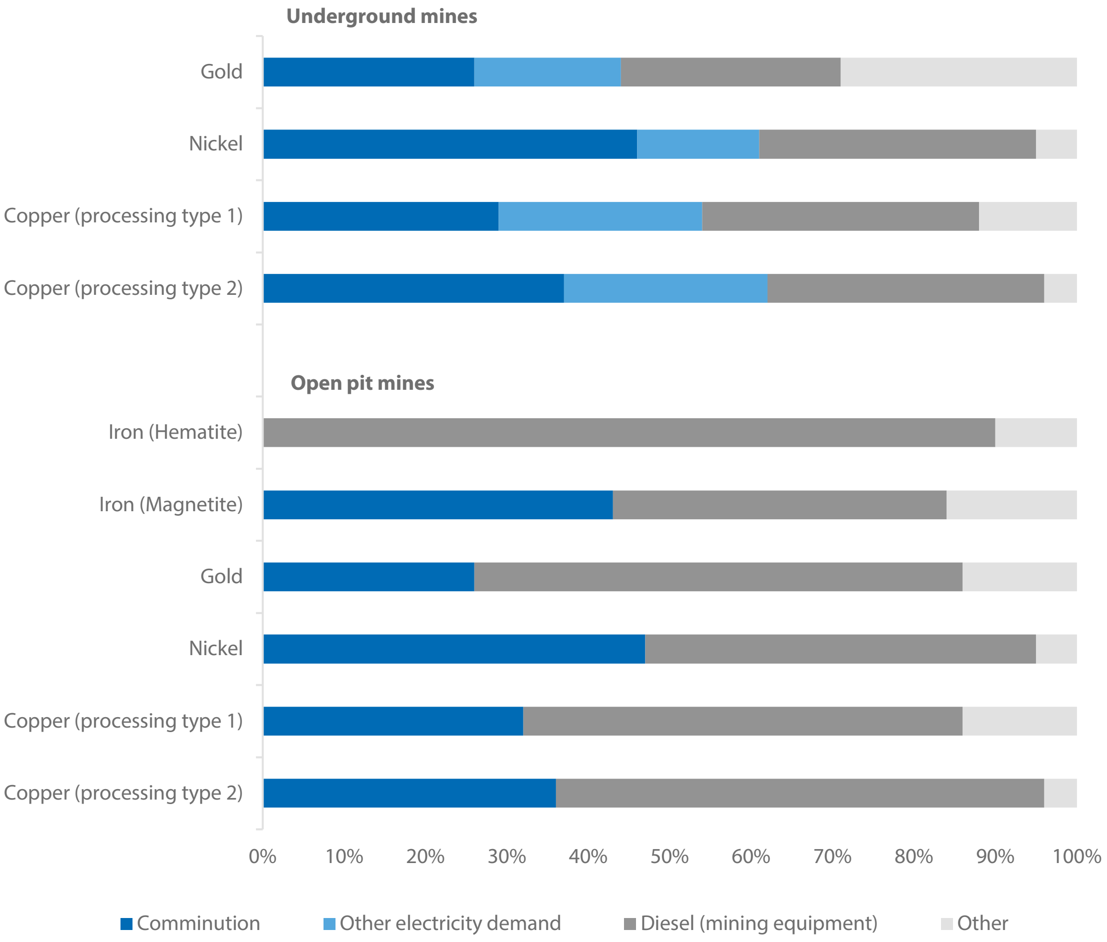
Mining processes vary significantly depending on, among other things, the specific commodity mined, the environment, and local geology. For example, metal mining requires significant power generation to crush rocks – known as comminution – with mills and other grinding equipment to break down rock material. Non-metallic or energy resource mining may adopt distinct approaches, such as solution mining. For solution mining, fluids are pumped deep underground to displace the commodity in place, which requires energy for pumps and, in some cases, to treat or heat the liquid solution.

For many mines, the decarbonising of electricity and thermal energy is not the primary hurdle for emissions reductions. Fossil fuels are used for some mineral processing techniques and the operation of heavy equipment and haulage vehicles, which poses a greater challenge in terms of carbon emission abatement compared to electricity needs. Up to 90% of an open-pit mining operation's energy demand can come from liquid fossil fuels used to power mining equipment or haulage vehicles to transport material at a mine site or from a mine site to a downstream processing facility.

Processing applications typically account for more than half of the electricity load for a mining operation that has processing on-site. The electrification of modern processing applications is expected to increase electricity demand at a mine site relative to other energy demands. In recent years, the market for mineral processing has been increasingly concentrated in a small number of countries for some specific commodities. NEA member countries are taking steps to capture more of the processing value chain domestically, and mining companies in these jurisdictions will likely adopt energy-intensive processes to meet this domestic demand for processing.

Open-pit, underground, and in situ mine types also have distinct energy consumption profiles. For example, underground mines need electricity for ventilation, which is not required for open-pit mines. Figure 2.5 below demonstrates the scale and variation of energy demands in the metal mining sector across various factors. There is notable variation in the energy demand profile of a mine site depending on the commodity being mined, the processing technique being used, and the minerology of the local deposit.

Figure 2.5: **Diversity of energy demand in metal mining as a function of commodity, processing, and local geology**



Note: Processing type 1 refers to leach processing with solvent extraction and electrowinning, while processing type 2 refers to the use of flotation plants with copper concentrators.

Source: Adapted from Allen (2021).

As the mining sector continues to make environmental progress, the heat and electricity load profile at mine sites is expected to evolve significantly as the sector adopts electrification, alternative transportation, and other process techniques. The inclusion of an SMR into a mine size is also expected to incentivise additional energy demand on-site and the improved utilisation of thermal energy. To decarbonise localised energy systems at respective mines, companies will benefit from a tailored approach for solutions that align with the particular needs and future plans of mining operations.

Electricity demand

Mining operations require electricity for a range of applications. Comminution accounts for approximately half of the energy consumption in the mining sector (Jeswiet and Szekeres, 2016). A single semi-autonomous ball mill used to process material through comminution typically operates with an electric motor on the order of 10-30 MWe.

In underground mines, ventilation means additional electricity requirements to ensure the safety of the workers and the proper functioning of equipment. Ground and rock temperatures increase with depth, which can be considerable at typical depths for underground mining operations, contributing to additional costs. Large volumes of ventilation air are pumped through the mine shafts to control the air temperature and quality. Depending on the environment of the mine and the depth, mining companies may also be required to chill or refrigerate the air in circulation, which contributes additional cooling power in the MWe-scale (Obracaj et al., 2022). Underground applications also require hoisting material and personnel in and out of the mine shafts and boring equipment.

Mining operations come with a complex and variable electricity demand profile. This demand fluctuates based on several additional factors, and according to the demand and environment on a seasonal, daily, and intra-daily basis. A mining operation's hourly electricity demand profile commonly fluctuates by more than 20% throughout a given day and from day to day. This variability in demand currently makes fossil fuel generation an attractive option for mining operations, where instantaneous demand can be satisfied in real time. It also emphasises the need for system cost analysis to identify a suite of suitable alternatives to satisfy the demand requirements of existing operations. The reliability requirements and the nuanced electricity demand profiles dependent on various temporal periods create significant constraints on the electricity generation options at a mine site.

Large mine sites considering SMRs to decarbonise operations have significant demand for power generation, often linked to processing activities. In multiple cases, mining sector stakeholders surveyed noted a demand of more than 80-400 MWe for a single existing operation. Many companies are also considering SMRs for greenfield operations to avoid emissions from next-generation mines needed to sustain the clean energy transition for the next 30 years.

End users also noted that electricity production currently represents a minority contribution to GHG equivalent emissions at mine sites and that the decarbonisation options for these applications are more apparent. However, those surveyed shared a common view that the overall demand for electricity in the mining sector will increase significantly as mining companies adopt electrification practices and other alternatives for their hauling vehicles, other heavy equipment, and processing activities.

Mining companies with off-grid mine sites identified plans to explore SMRs, or a series of micro-SMRs, among a range of potential energy solutions to replace diesel consumption and heavy fuel oil. Electrical energy requirements for these sites vary significantly, ranging from 2 to 50 MWe and, in some cases, up to 150 MWe of electrical demand.

Several mining companies operate mines connected to national or large regional electricity grids. These grid-connected mines, while having access to more stable energy sources, still require additional on-site power generation. Mining companies noted that this need arises from a combination of factors, including the reliability and predictability of grid supply, specific energy demands of mining operations, and the pursuit of operational independence. The diversity in electricity requirements underscores the need for flexible and tailored energy solutions for mining operations.

Thermal energy demands

Mining operations could also benefit from thermal energy at a mine site to support district heating of facilities, thermal energy storage to support to enable load following and new product stream, and additional thermal energy applications related to mineral processing or remediation.

Engagement with mining sector stakeholders indicates that for most mining operations, thermal energy demand is currently limited to low-grade applications, such as using waste heat from thermal generation as a source of district heating for the mine facilities. Typically, sufficient thermal energy is captured from waste heat produced from the gen-sets used to produce the electricity for the mine. This cogeneration aspect is pervasive in global mining operations and can serve a critical need for worker safety in regions with harsher climates. For small off-grid mining applications thermal energy demand is also modest compared to electricity demand. In particular, respondents noted that thermal energy demand was less than 15 MWth for remote mines with a corresponding electricity demand of less than 50 MWe. The entirety of this thermal energy demand is attributed to the use of low-grade heat for district heating applications.

The use of thermal energy in mining operations is limited. In solution mining, thermal energy is occasionally used to treat the solution thermally before injection into the deposit. In underground mining, thermal energy can also be used to manage the temperature and operating conditions of the mine, which ensures the safety and working conditions of personnel and equipment.

Downstream mineral processing also demands significant thermal energy, some of which are low-temperature applications such as thermal treatment in solution mining, while other downstream mineral processing techniques require high temperatures, such as iron smelting.

Very high-temperature processes are limited to downstream activities such as copper smelting and the production of steel. These processes are more commonly located in centralised processing facilities instead of at a mine site. In the case of steel production from iron, the current typical process of using a blast furnace requires temperatures of 1 500°C (Sun et al., 2022), which poses a significant decarbonisation challenge as there are few alternatives to the combustion of fossil fuels that achieve high smelting temperatures at those levels. Some other options exist, such as using electric arc furnaces or directly reducing iron to extract iron from its ore below this melting point, but these options are currently restricted. A market evaluation for SMRs to support downstream mineral processing is beyond the scope of this study.

Finally, if thermal energy is available and economic, opportunities exist to adopt more environmentally friendly remediation activities. Many traditional mineral extraction activities often use water and chemicals to extract minerals from ores. These methods can generate liquid or wet waste, including toxic tailings that must be managed and treated. Thermal energy from natural gas is commonly used to remove moisture from mine tailings to create a dry, stackable product and reduce the need for tailings ponds at mine sites. This potentially reduces the contamination of water sources and decreases the ecological impact on surrounding areas. In some mining processes, thermal energy could be used to extract minerals more efficiently and produce less waste (IAEA, 2023a).

There is a wide range and scale of thermal energy applications in the contemporary mining sector and additional opportunities to adopt processes that could use thermal energy to improve the environmental performance of the mine in the future. This variance underscores the importance of an adaptable and flexible approach in decarbonising the mining sector. Thermal energy can also be used in heat storage systems to enable greater flexibility in the energy system of a mine. Mining companies should explore opportunities to adapt existing processes and quantify the associated thermal energy needs in such operations to identify the feasibility and scale of using SMRs to supply thermal energy.

Box 2.2. **Deep decarbonisation of potash mining**

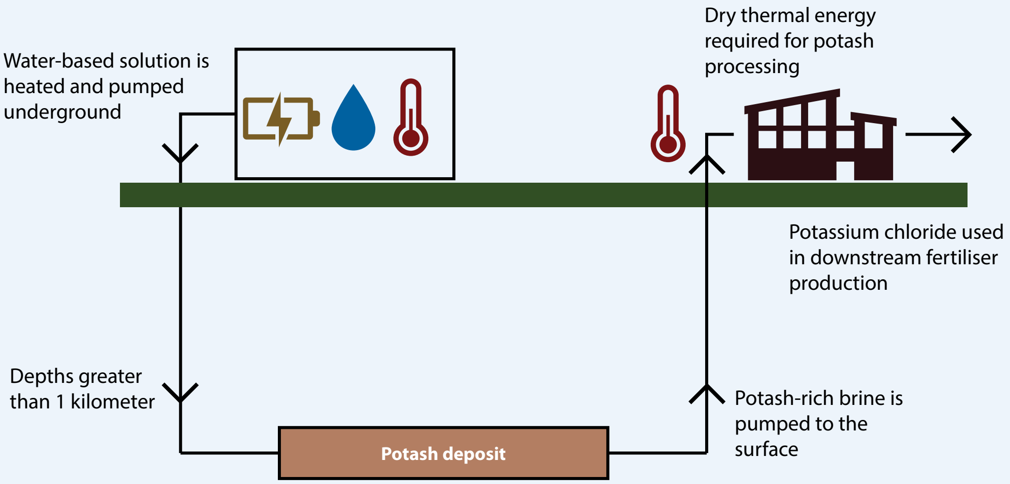
Non-metallic and resource extraction mining often have distinct energy requirements compared to open-pit and underground metals mining. In cases where the requirement for haulage is negligible compared to the broad energy demands of the mine, there is potential for near-term deep decarbonisation by replacing fossil-based energy supply with a low-carbon thermal energy source. Solution mining to extract potash is one example.

Potash refers to potassium-bearing salts, which are primarily used to produce fertiliser. Global potash demand represents a market exceeding USD 50 billion, with a growth rate of 4-5% per year linked to global population growth and the increasing need for sustainable food production. The geographical distribution of potash deposits and extraction operations is very concentrated in a small number of regions, which drives price volatility because of currency exchange rates, geopolitical factors, and other local impacts. In 2021, Canada, Russia, Belarus and China accounted for 80% of the world's potash production. Canada, which accounts for approximately one-third of global production, mines Potash at only ten facilities in the province of Saskatchewan.

Two methods for potash mining are employed depending on the accessibility of a deposit. In general, conventional open-pit or shaft mining techniques are typical for shallow deposits, while solution mining is adopted for deeper deposits.

In solution mining, the requirement for thermal energy in the form of steam and dry heat is the largest source of GHG emissions, which currently relies on the combustion of fossil fuels such as natural gas. First, thermal energy is used to heat a water-based solution, which is then pumped underground to dissolve the water-soluble potash in the ore body into the mobile solution. The desired fertiliser feedstock is then pumped to the surface as a brine, as shown in Figure 2.6 below. Once on the surface, dry thermal energy removes the water from the potash.

Figure 2.6: **Illustration of thermal energy requirements in solution potash mining to support the production of potassium-based fertiliser**



Beyond these thermal energy demands, almost all the remaining energy needs for potash mining solutions come from processes that currently use electricity. The need for haulage vehicles in solution mines of this type is minimal, and diesel consumption to power mining equipment and vehicles accounts for only 1% of emissions.

If SMRs prove to be a predictable and economical source of both thermal energy and electricity for mining operations, there is an opportunity for deep decarbonisation of both brownfield and greenfield potash mining operations that use solution mining.

Source: GVR, 2021; NRCan, 2022; and FC, 2023.

Clean energy alternatives

Currently, most energy consumed at a mining site comes directly from the grid as electricity or from fossil fuels such as natural gas, diesel, and heavy fuel oil. Pressure from shareholders and the public to improve environmental practices at publicly traded companies represents a significant driver for adopting clean energy alternatives by mining. More than 80% of mining sector representatives in the survey reported that their companies have targets to achieve net zero carbon-equivalent emissions by 2050 or earlier, with some targeting a timeline of net zero emissions by 2030.

To date, progress towards decarbonising the mining sector has been restricted to electricity production and to non-electric applications that have become electrified.

The mining industry has taken steps to improve its environmental performance through its support for renewable energy. The KGHM Sierra Gorda copper and molybdenum mine in Chile is one example. The company announced in January 2023 that it would contract for renewable energy representing 100% of its electricity requirements (Moore, 2023). Replacing their energy supply enabled the Sierra Gorda mine operation to reduce net emissions by 1 million tonnes of CO_2 annually. The Sierra Gorda mine uses haulage vehicles to transport ore to a processing plant, which then consumes electricity for comminution and additional ore material processing. Electricity is secured through a supply contract from solar photovoltaic, wind, and hydro sources operated by AES Andes, along with storage systems based on lithium batteries.

Progress towards the electrification of specific processes has also advanced in recent years. The Boliden Aitik mine in northern Sweden provides a notable example of electrification, piloting electrified transport since 2018 to replace a portion of the haulage vehicle fleet and reduce transportation-related emissions by 15% over the life span of the mine. In northern Finland, Agnico Eagle’s Kittilä underground gold mine is another example, where electric haulage vehicles and drilling units have been successfully deployed and tested since 2020. When used at underground mines, electric alternatives to diesel equipment also improve air quality and may improve worker safety by reducing the production of hazardous gases below the surface.

Relying solely on intermittent renewable sources like wind or solar is impractical due to the reliability requirements for mine sites amid complex energy demand profiles (Votteler and Brent, 2016). Therefore, while deep decarbonisation of the mining sector will require continued progress in adopting clean electricity and electrification, it will also require innovation and alternatives to existing hard-to-abate processes. In addition to SMRs, alternatives like hydrogen and electrification, such as renewable natural gas or diesel, are also being evaluated on a limited scale.

While this study focuses on mining, downstream mineral processing also represents a decarbonisation challenge for the mining sector, given energy needs such as high-temperature blast furnaces for processing iron, copper, and other metals, reliant on natural gas and coal combustion for industrial heat. Direct reduction could replace a blast furnace using hydrogen to reduce iron below the metal’s melting point in the case of iron. In the case of copper, an electric arc furnace offers solutions to replace existing high-temperature processes with fossil fuels.

The production and use of hydrogen for synthetic fuel production, fuel cells, or hydrogen combustion engines presents additional options to power haulage vehicles and other heavy equipment (Hatch, 2022). Hydrogen also shows promise to support downstream mineral processing activities. Given the variation of demand across a day, week, and even season at mine sites, and considering the expected integration of intermittent renewables, mining sites could produce hydrogen during periods of low demand. Combined with the electrification of the mining sector, the power generation needs of high-temperature steam electrolysis or thermochemical processes provide yet another potential application for SMRs in the mining sector (NEA, 2022).

Finally, SMRs could help with the necessary integration of a range of clean energy technologies. For most micro-grid optimisations where reliability is a critical parameter – as is the case for off-grid mining applications – hybrid approaches often demonstrate the most value with baseload generation such as fossil fuels, hydro generation, or SMRs as a necessary and practical complement to renewable energy technologies (Balaji and Gurgenci, 2019; Hatch, 2022; Macdonald and Parsons, 2021; Poudel et al., 2021). For instance, electricity generated from SMRs could be used to produce hydrogen for energy applications, demonstrating an integrated approach to energy management. This integrated strategy reflects a shift from isolated energy solutions to a more systemic view, considering complementary aspects of different energy sources.

There is a wide range of energy requirements at mine sites and a wide array of potential clean energy alternatives that mining companies could explore to achieve emissions reduction targets. The solution for each respective mining operation will require a unique assessment, resulting in distinct solutions.

Energy decision drivers

Several factors emerge when deciding which energy options to pursue as an alternative to fossil fuels at existing facilities or in energy planning for future greenfield operations.

The primary influential energy decision-making factors include economic considerations, environmental impacts, and the suitability of energy generation technology for the operational needs of the mine. Companies also consider supply chain readiness and clear and long-term policy support for clean energy alternatives. The survey typically viewed these factors as more important than other energy decision drivers, such as the ability to scale the asset with changing demand.

Long-term price predictability of energy supply was also noted as an important factor, with responses varying depending on the region. In particular, European mining companies highlighted a higher relative importance of future price certainty compared to North American counterparts. There are considerations for both the ability to ramp operations up and down in response to commodity prices, and the benefit of predictable operating costs from as a result of low fuel costs. In either case, greater operating cost certainty may enable improved optimisation to steady the mine output and in turn reduce price volatility in the downstream commodity market.

In contrast, stakeholders in North America primarily emphasised the importance of long-term policy predictability and the need for clear regulatory pathways – an aspect emphasised consistently regardless of jurisdiction. Responders to the survey generally identified the lack of clarity and certainty in policy and regulation to make informed decisions on long-term investments as a barrier to innovation, including in areas like SMRs.

Environmentally, organisational ESG requirements serve as the primary driver for adopting clean energy alternatives at mine sites, of which emissions reduction associated with operating the mine is a primary focus. End users noted that environmental impacts may be improved beyond emissions reductions if abundant clean energy is available. Waste management was also pointed out as an important ecological factor critical to resolving new energy assets, including spent nuclear fuel, solar panels, and commercial energy storage once the assets reach end-of-life.

Responders to the survey noted that the energy asset's suitability to the mine's operational needs is important. The ability of the energy asset to reliably satisfy the required energy demand profile of the mine emerged as a recurring theme in discussions and survey responses with mining sector end users.

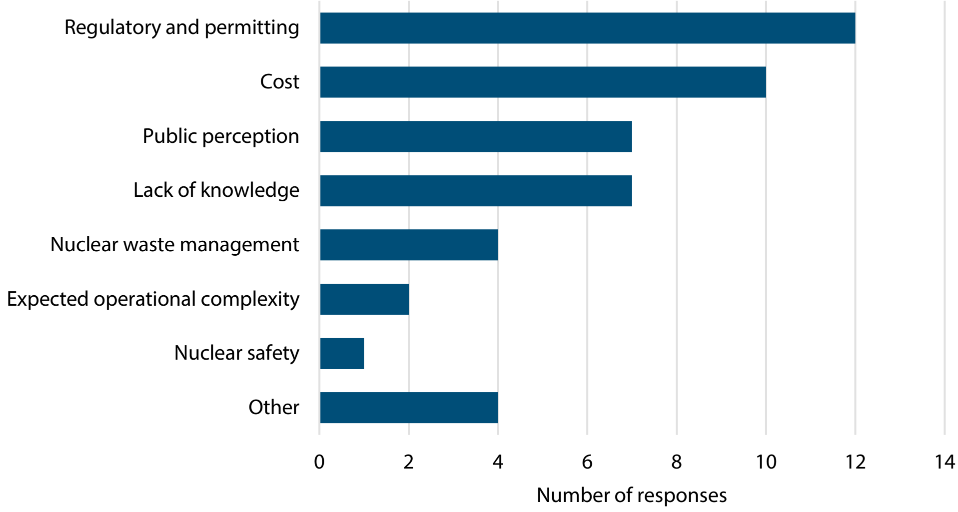
In the case of underground mines, responders cited constant electricity as essential to power both ventilation and mine site access, which concerns worker safety. From a non-safety perspective, downtime at a mine site is costly due to the capital-intensive nature of mining. Additionally, heavy equipment can become damaged in sudden power loss (e.g. a mill used for comminution in mineral processing.) As a result, mining operations must ensure sufficient backup generation on-site in standby mode to ensure that energy demand can always be met, including in emergencies. Responders to the survey also noted their apprehension of future reliability issues due to the energy transition happening at a regional or national scale, impacting the reliability of electricity supply in the connected grid.

The operational complexity of clean energy alternatives was not viewed as a barrier relative to other existing complexities associated with operating a mine (e.g. fluctuating operational costs and commodity prices, evolving policies related to sustainable mining and critical mineral supply and predicting and responding to demand signals). Nevertheless, simplicity presents an attractive quality to reduce operational costs associated with site management and infrastructure maintenance. For some remote mines that self-generate electricity, the maintenance of transmission lines after construction is a factor in the investment decision beyond upfront capital costs associated with developing transmission lines.

Considerations for SMRs

For SMRs in particular, the primary barriers identified related to the potential deployment of SMRs at mine sites are cost, regulatory aspects, and public perception. Other obstacles to implementing SMRs include a lack of knowledge about nuclear energy and the need for robust waste management practices for incorporating the nuclear fuel cycle into mining operations. Notably, mining sector stakeholders expect the safety of the SMR technologies to be sufficient and the operational complexity of including nuclear energy among the existing mining processes at a mine site to be manageable.

Figure 2.7: **Main perceived barriers for mining companies to transition to nuclear energy or SMRs according to interview and questionnaire responses**



Uncertainty around costs is considered one of the biggest reasons for the diversity of options explored by the mining sector for the energy transition, which includes uncertainty around cost structures for SMRs compared to fossil fuel assets. End users noted that return on investment and price certainty are the most critical factors for adopting clean energy alternatives at mine sites. End users also noted that acceptable upfront capital costs would be required amid already high costs for mining operations. Due to remaining uncertainty in costs for SMRs, most mining executives are waiting for the first-of-a-kind SMR demonstration project applicable to operations in the mining sector. Mining sector stakeholders could be expected to increase the uptake of SMR deployment immediately following a successful technology demonstration and corresponding operating model.

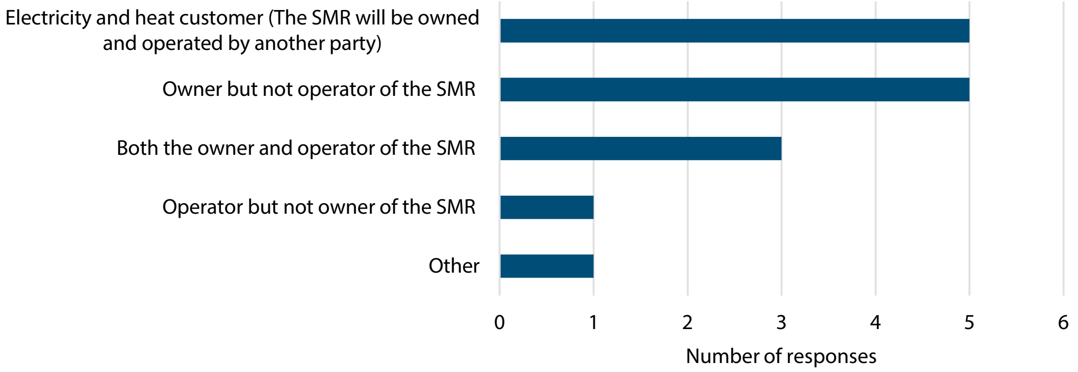
The timeline for commercialisation and supply chain construction is viewed as a critical component of selecting an SMR project. Mining sector end users also indicated that the current timeline for the commercialisation of SMRs fails to align with the immediate energy needs of the mining industry. The need for clean power at a mine site to replace diesel, heavy fuel oil, and other reliable fossil fuels is immediate, with the commitment from mining to reduce emissions by 2030 and decarbonise entirely by 2050. Given timelines for widespread SMR deployment post-2030, mining companies continue to explore other options to achieve near-term environmental performance targets.

Concerns were also expressed with regard to the robustness of the nuclear energy supply chain, which extends beyond material requirements to knowledge development and the ability to train staff appropriately. This situation requires extensive investment in the energy sector, including training personnel for nuclear operations.

Gaining social licence and community acceptance for SMRs was considered vital. Responders to the survey and interviewees emphasised the need for early and extensive engagement with communities, including regions with a history of uranium mining (NEA, 2023). Mining sector representatives at advanced stages of SMR deployment noted the vital importance of public acceptance in advancing a project. The location of SMRs at mine sites may vary from the industrial or mining area due to safety concerns and public opinion. Additional opportunities to better utilise the heat and electricity from the co-location of an SMR will open further with greater public awareness and acceptance. Notably, public opinion research in Alaska suggests that the perception of negative environmental performance in the mining sector and other issues with neighbouring communities adds a layer of complexity when working to build public confidence in the suitability of nuclear energy in a mine's energy portfolio, which is expected create additional project risk, even if micro-SMRs are identified as a suitable solution (University of Alaska's Center for Economic Development, 2020).

From an operational standpoint, mining sector respondents identified a range of potential business models for SMR operations. Almost all mining sector end users engaged in this report specified a disinterest in operating the SMR asset themselves, preferring various ownership models. While a large group of end users intend to purchase heat and power from a secondary entity as owner and operator of the SMR, others were equally supportive of models with the SMR as an asset of the mine run by an operator. A smaller subset of respondents were interested in exploring in greater detail the option of becoming both the owner and operator of the SMR for the mining operations.

Figure 2.8: **Possible business models being considered by mining companies, as identified through interview and questionnaire responses**



Regardless of the ownership model, there was clear interest from the mining sector that SMRs appear to be a suitable technology in many situations, assuming that they are economically competitive and other risks can be reasonably mitigated. Given the current technological and commercial readiness of SMRs, some companies are planning to monitor the initial deployment and testing of the technology with the intent to adopt SMRs for future projects and are considering space requirements and grid connections at their sites already for this need.

Size and lifetime synchronicity

As the energy demand at a mine site fluctuates significantly on a seasonal, daily, and intra-daily basis, risks are associated with curtailing or shedding excess electricity produced from an SMR due to the capital-intensive nature of nuclear energy projects. In contrast to electricity produced by fossil fuels, which require relatively modest upfront capital costs compared to their enduring operating and fuel costs, an SMR has a significant upfront capital cost and a relatively small fuel cost. This high upfront capital cost and small marginal cost of operation are shared among all low-carbon energy sources, which suggests cost inefficiencies if the energy asset is overbuilt.

Similarly, a project risk has been identified with the potential asynchronicity between the operational timeline of a mine and the expected lifetime of an SMR as an energy supply (Canadian SMR Roadmap, 2018). This is especially true for brownfield locations looking for opportunities to reduce emissions. Through previous engagement with mining sector end users operating in remote areas, representatives of remote mining operations in Alaska expressed that the cost of new infrastructure combined with the limited life of a mine suggests an opportunity to deploy micro-SMRs at new mining projects under development rather than as a replacement to existing generation at existing mine sites (University of Alaska's Center for Economic Development, 2020).

Engagement with mining sector end users for this study suggests that the sizing challenge related to a mine's output and operating life is not expected to be a significant hurdle, as the scale and life of a mine can be strongly influenced by energy availability. An energy asset can be sized to a mine, but a mine can also be sized for an energy asset. In particular, if energy is readily available, it will impact the economics associated with an expansion or on-site processing, which may affect the overall long-term return on investment from a mining operation. Mining companies have also identified that modularity of supply is important to enable mine expansions or additional on-site processing and to reduce production when commodity prices are not favourable to continue operating.

For grid-connected mines, stakeholder engagement with mining sector end users identified off-take agreements with grid operators and utilities to be a solution to mitigate risk associated with the sizing synchronicity between the energy output of an SMR and the energy demand of a mine. The ability to sell electricity to a distributed electricity grid significantly minimises sizing risk associated with the energy supply, as excess low-carbon intensity electricity can be sold to a national grid instead of curtailing supply. As electricity grids face decarbonisation challenges in many jurisdictions, off-take agreements also offer a supply of clean electricity to meet decarbonisation goals.

The approach of using off-take agreements to reduce the risk associated with the initial deployment of SMRs at mine sites has been adopted by Rosatom in Russia. Rosatom has an agreement to provide power to a Seligdar's gold mine in the region of Yakutia using the RITM-200N SMR, which is a land-based version of the RITM-200 pressurised water reactor design that is already licensed and in operation on the icebreaker ships in Russia. Rosatom has also secured an off-take agreement for up to 50 MW with the local government of Yakutia to ensure power for the development of the gold deposit while also supplying energy at an affordable price to isolated consumers in the region.

It is recommended that grid operators work with mining companies through off-take agreements to enable initial SMR deployments by removing project risk associated with sizing and curtailing energy produced by the energy asset.

While off-take agreements are a useful tool to potentially reduce project risk related to the size and lifetime synchronicity of initial SMR projects in the mining sector, they are not possible for off-grid mining operations isolated from a primary grid. In this case, mining companies may choose to work with nearby communities that could benefit from the excess energy, or adopt innovative SMR designs and energy storage to operate flexibly.

Mining sector end users have noted their interest in exploring the possibility of SMR technologies that are capable of ramping power output up and down to meet instantaneous demand changes and transportable SMRs where the asset can be transported off-site at the end of the mine life and either moved to another mining project owned by the company or sold to a third party to utilise the remaining life of the energy asset.

The operational flexibility enabled by these proposed solutions significantly reduces risk in the mining sector. However, mining operations will need to be assessed on a case-by-case basis to determine the size of a given energy asset. Future analysis on the role of SMRs in the mining sector may benefit from additional analysis on practicalities associated with nuclear energy waste management and the logistics of transporting an SMR at the end of its operating life.

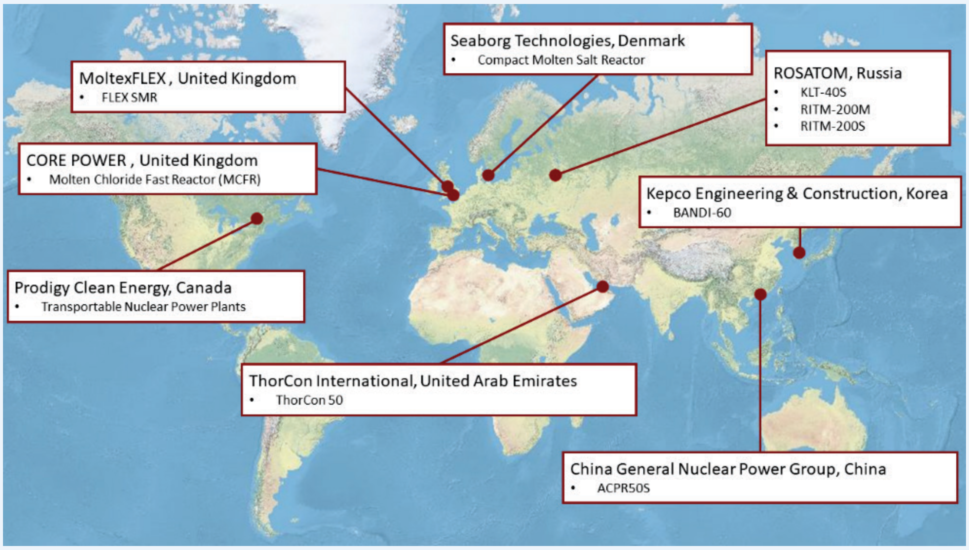
Box 2.3. **Floating nuclear power plants**

SMR innovations have a range of possible configurations, including marine-based or floating SMRs. Certain SMR designs, including microreactors, may be well-suited to be configured into a marine-based system that can be used for both grid-scale and remote off-grid sites. For example, micro-SMRs can be fabricated and assembled off-site and transported to a remote mine site to provide heat and power for mining applications onshore.

Floating nuclear power plants have different siting requirements for SMR deployments and allow the SMR to be transported off-site at the end of the mine's project life. Given the mobility of floating nuclear power plants, concerns related to licensing, regulation, insurance, and operation in international waters are currently being addressed through efforts by the International Atomic Energy Agency (IAEA). Given the demand and cost associated with the transportation of material in the mining sector, nuclear-powered marine propulsion may also benefit the industry. The IAEA conducted a preliminary study on transportable nuclear power plants' legal and institutional issues in 2013 and is currently working on a follow-up study on factory-fuelled transportable nuclear power plants.

The NEA SMR Dashboard establishes that marine-based SMRs are being considered for a range of heat and electricity applications, as shown in Figure 2.9. Marine-based SMRs are being advanced in China, Denmark, Korea, Russia, the United Arab Emirates and the United Kingdom, and floating power barge technology suitable for SMRs is also being advanced in Canada (NEA, 2024).

Figure 2.9: **Global marine-based SMR technology development and deployment**



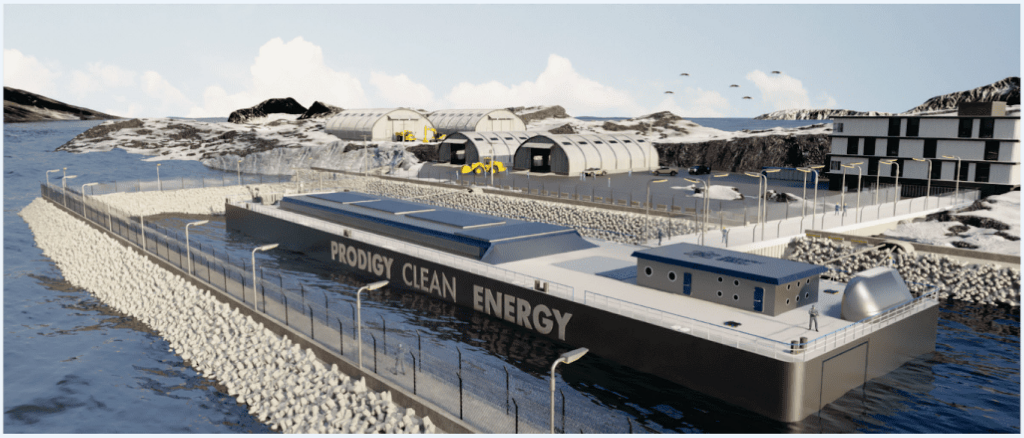
Source: NEA, 2024; IAEA, 2023b.

In Russia, the KLT-40S pressurised water SMR has been operating since 2020 as part of the Akademik Lomonosov floating nuclear power unit, and Rosatom is developing a series of floating SMRs based on the RITM-200 reactor concept that is already licensed for marine propulsion and in operation on the icebreaker ships Arktika, Sibir, and Ural (NEA, 2024). This includes the RITM-200S, which is being developed to meet the local needs of remote regions in Russia, including off-grid mining. In 2021, the Russian government concluded a competitive selection process to select a supplier of heat and electricity for the Baimskaya copper mine and mineral processing facility in Cape Nagleynyn, Russia, owned by Kaz Minerals. The proposal to deploy a series of marine-based RITM-200S units to power the mine was ultimately selected over an alternate option to develop a floating liquefied natural gas power plant, with the first unit expected to be online as early as 2027.

In China, the first demonstration of the ACPR50S floating nuclear power plant is under construction, providing power for drilling platforms in the Bohai Sea. Future applications for floating nuclear power plants in China include deep-water oil and gas exploration in the South China Sea.

The Canadian company Prodigy Clean Energy is developing a marine deployable power station for micro-SMRs targeting remote applications and a grid-scale power station, as represented in Figure 2.10. Prodigy is working with SMR technology developers to explore and inform the development of a regulatory framework to address the licensing and deployment of a power station.

Figure 2.10: **Rendering of the Prodigy Microreactor Power Station Transportable Nuclear Power Plant concept**



Source: Prodigy Clean Energy.

Denmark, Korea, and the United States are also engaged in developing floating nuclear power plants and are engaging internationally, bilaterally, and with shipping regulation and classification authorities such as the American Bureau of Shipping on the benefits and opportunities of developing floating and mobile floating nuclear power plants.

Source: NEA, 2024; IAEA, 2023b; and IAEA, 2023c.

Regulatory, permitting, and social licence

For mining service users, the regulatory and permitting process for SMRs as part of the existing permitting process to operate a mine is a concern. The concern is that this integration of SMR permitting with mine permitting could potentially delay the startup of mine operations, especially across a company's global operations that face varied technical, logistical, and regulatory challenges across different jurisdictions. The complexities and uncertainties in these processes, including the long timelines required for securing the appropriate licences, add project risk. These challenges are compounded by the unpredictability of public perception, which can also influence timelines.

Despite these hurdles, end users perceive the timelines for SMR deployment to align reasonably well with the existing permitting processes for new mining facilities. This is mainly because new mining projects require several years to navigate environmental and regulatory approvals.

Given the anticipated deployment timeline of SMRs and the significant cost penalties associated with delaying permitting for mine sites, a need for streamlined permitting was identified. This process should consider the unique requirements of the mining sector and the specialised nature of becoming a nuclear operator. The current landscape, where nuclear operators are largely limited to centralised facilities producing power for the electricity grid, is not directly applicable to off-grid mines that may adopt micro-SMRs.

A recommended business model involves SMR vendors or third-party operators taking the lead in the licensing and permitting process for the SMR. This approach would leverage their experience with nuclear regulatory authorities and reduce the burden on mining companies, allowing them to focus on their core activities without being bogged down by additional licensing and regulatory processes.

There is a consensus on the importance of aligning stakeholders, including government entities, utilities, and private companies, to mitigate risks and streamline the transition to SMRs, while specific concerns vary by region. For instance, companies operating in jurisdictions with positive public opinion towards nuclear energy, such as Poland, may face dramatically different obstacles that impact timelines and complicate the permitting process, such as in Australia. The international nature of many mining operations, with facilities in multiple jurisdictions, underscores the need for information sharing and transparent regulatory frameworks.

Operating globally requires engagement in diverse regulatory environments, which requires considerable technical expertise and robust supply chain logistics. The mining industry emphasises the need for design standardisation as well as transparent information sharing from initial SMR projects. This transparency is crucial to facilitate the learning and adoption of SMRs across the industry, allowing companies to navigate these jurisdictional differences more effectively.

Key findings and recommendations

This analysis of mining sector end user needs and perspectives, grounded in structured interviews and surveys, reveals the complexity of technical, business, and operational requirements for mining operations globally. These demands vary significantly depending on the commodity being mined, the availability of electricity, the type of the mine, the processing requirements, and the localised environment. Individual mine sites have specific requirements, and the solutions available to each mining company to improve their environmental performance and reduce emissions are highly variable depending on their particular situation.

The electrical demand profile of mining operations is complex, and replacing existing supply with clean energy technologies will be challenging. Electricity reliability is essential for worker safety and maximising mine productivity, and mining companies typically pay a premium and maintain backup generation systems in standby mode. The electrical demand profile is expected to evolve as mining processes become electrified, and there will be a persistent demand for thermal energy in most cases. This demand may arise from lower grade needs such as district heating or be directly utilised in mining, processing, or remediation processes.

The addition of an SMR at a mine site may also incentivise additional energy consumption and thermal energy storage as a means to improve the stability of an energy system. Regional connections with other energy end users outside the mining project, such as communities and new industries may offer a broader long-term solution to balance localised demand profiles.

There is a clear interest in the role of SMRs in supporting the decarbonisation of the mining sector due to their potential to offer abundant, consistent, and reliable energy that meets the operational needs of mines, especially for remote mining operations or those with intensive energy demands for mineral processing. The interest in SMRs within the mining sector is primarily motivated by the need to align industrial activities with organisational ESG commitments and ensuring predictable operating costs, balancing environmental responsibilities with economic feasibility.

While uptake in the mining sector is expected to be significant, several uncertainties will need to be addressed during first-of-a-kind deployments of SMRs at mine sites. The diversity of energy needs across mining operations indicates that a universal solution is not feasible. Prominent concerns about costs, regulatory complexities, public perception, and operational integration were raised. Establishing clear regulatory frameworks and effective waste management practices are essential for successfully integrating SMRs into mining operations.

It is recommended that mining companies continue to explore and evaluate SMRs as part of a broader strategy to meet their ESG objectives. Mining companies should quantify and communicate their specific electricity and thermal energy needs and work with the nuclear sector to assess the suitability of SMRs for their particular operations. Mining companies should generally adopt a more holistic approach in their energy option analysis and evaluate SMRs as part of an integrated and complementary clean energy system involving hydrogen, renewables, and energy storage.

Policymakers and regulators are encouraged to develop clear and efficient regulatory pathways for adopting and implementing SMRs in mining operations. They should ensure that these frameworks accommodate the unique aspects of mining operations and enable financial and operational flexibility while addressing public and environmental safety concerns.

For SMR technology developers and utilities: Collaborate closely with mining companies to identify technical solutions for specific mining contexts. Focus on transparent communication about the costs, operational requirements, and safety aspects of SMR technology to build trust and facilitate adoption. As mining companies generally wish to avoid operating an SMR themselves, explore a business model where SMR vendors or third-party operators with experience progressing with nuclear regulatory authorities lead the process of securing the licence to operate and other permitting required to deploy an SMR at a mine site.

Grid operators, regional governments, and utilities should work with mining companies and agree to purchase excess electricity generated from a first-of-a-kind SMR through off-take agreements to reduce the risk associated with initial projects that would adopt SMRs for mining applications.

Finally, energy and environmental researchers and academic institutions should continue studying the long-term implications of integrating SMRs into mining operations and use the opportunity to advance the training of skilled workers with knowledge of nuclear energy.

By addressing these recommendations, the mining sector can make significant strides towards a more sustainable and efficient energy use, contributing to the broader transition to clean energy globally.

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Chapter 3. **Off-grid mining**

Introduction

The primary market for SMRs in the mining sector is to serve large mines with significant and reliable low-carbon power demands. There is also a distinct opportunity for SMRs to provide heat and electricity to off-grid mining operations due to the current elevated costs associated with energy generation in remote areas.

While most mines are found in regions far from urban areas that could be considered remote, there are a subset of remote mines that self-generate their required energy as it is not cost effective to build transmission infrastructure to connect the mine to an electricity grid. The quantitative assessment in this chapter will focus on these off-grid mines in particular and evaluate the energy alternatives associated with operating a mine in a remote area.

Due to the lack of connections to centralised electricity grids, off-grid mines typically use diesel or heavy fuel oil (HFO) to power their operations. Transportation and fuel costs for mining operations that use diesel or HFO are significant drivers of the operational costs of mining. The Mining Association of Canada identifies a 60% increase in operating costs in remote mines compared to comparable centrally located facilities, and infrastructure costs more than double (Marshall, 2022). The price volatility of diesel and HFO fuels can also pose financial risks for mining operations and add uncertainty to financial forecasting.

Besides the cost aspect, these fuels emit greenhouse gases and other pollutants, contributing to climate change and local environmental degradation. In recent years, there has been pressure on mining companies to transition away from the use of diesel and HFO as governments, investors, and the general public advocate towards reducing carbon emissions and promoting cleaner energy alternatives in industrial sectors, including mining.

Off-grid mines typically have much smaller power requirements compared to grid-connected mines, representing an opportunity for micro-SMRs. Notably, off-grid mines that self-generate their own electricity are also found to have large power demands, similar to grid-connected mining operations, with hundreds of MWe of installed generating capacity of diesel or HFO fuel (Banerjee et al., 2014). The analysis in this Chapter focuses on the opportunity for micro-SMRs for smaller off-grid mines.

Small off-grid mines that may be suitable for micro-SMRs represent a small portion of the global mining activity. Due to the high infrastructure and operating costs associated with their remote nature, they typically focus on high-value commodities such as gold, diamonds, and an emerging trend towards rare earth elements and other critical minerals. In addition, these off-grid mines are typically characterised by logistical challenges and infrastructure vulnerabilities associated with their remote nature.

A representative off-grid mine

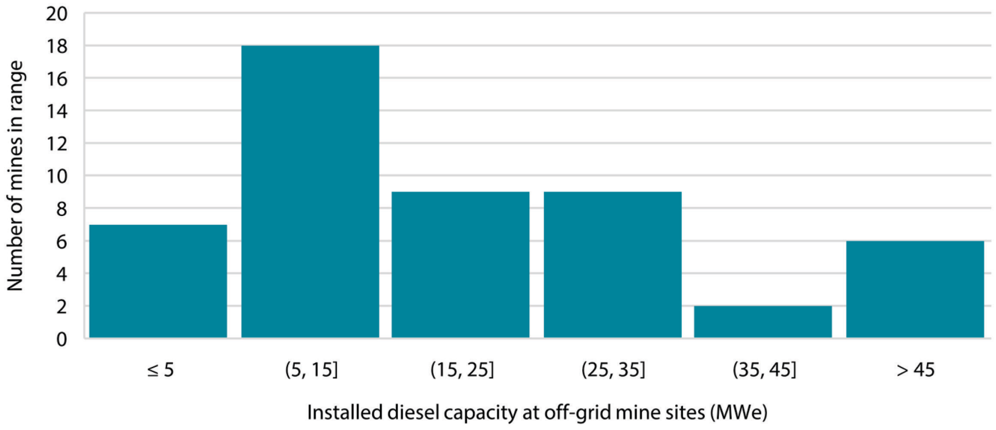
The power demand of a representative self-generating mine was determined using aggregate data of installed thermal generation capacity from 51 existing or planned off-grid mines across nine countries in Africa, Oceania, and North America. The median installed capacity was determined to be 16.0 MWe, with a mean value of 31.3 MWe. A distribution of the installed capacity at these 51 mine sites is presented in Figure 3.1. For 34 of these mines, the project lifetime was also available. This subset of existing or planned off-grid mines was determined to have a median lifetime of 16 years, with a mean value of 20.2 years.

These characteristics may increase significantly as mines continue to adopt electrification and other alternative processes to reduce sector-wide emissions. Nearby communities could also connect to a localised electricity grid at the mine facility to benefit from available energy, increasing the predicted power requirement and project timeline further.

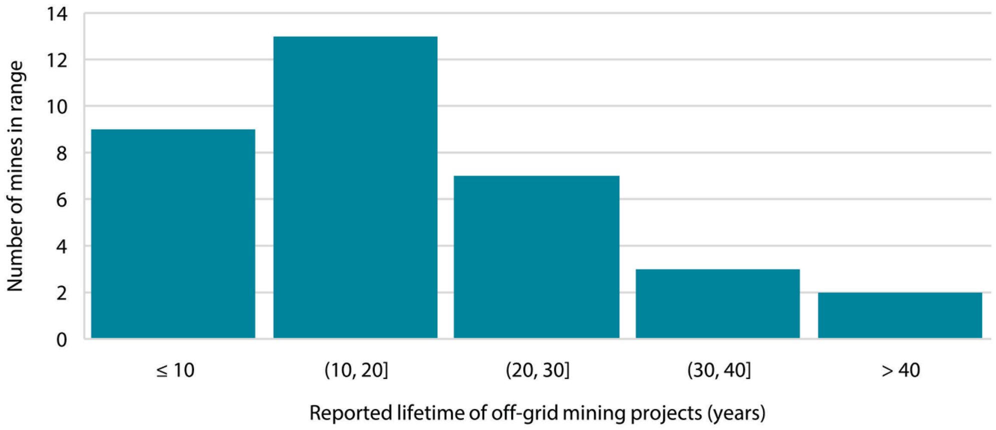
Median values are used in the following quantitative assessment to estimate the total potential power demand for the remote mining sector. As a consequence, the subsequent market size assessment for micro-SMRs excludes off-grid mines that have very large power requirements exceeding 100 MWe of installed thermal generating capacity or more, which may be more suitable for larger SMRs.

Figure 3.1: **Distribution of installed thermal capacity and project lifetime of 51 existing or planned self-generating mines**

a) Distribution of installed capacities of 51 existing or planned self-generating mines



b) Distribution of mine lifetime for 34 existing or planned self-generating mines



Source: Aggregate data from ZE, 2023; AECOM, 2014; NRCan, 2018; Bayomy et al, 2023; Froese et al., 2020; WC, 2016; Banerjee et al., 2014; NS Energy, 2020; University of Alaska's Center for Economic Development, 2020.

There are also a significant number of mines that are connected to the electricity grid that self-generate a portion of additional electricity. Mining operations may self-generate their electricity for reliability reasons, proximity to the electricity grid, to ensure electricity price predictability, or to meet peak demands during specific intervals. Backup generation, or additional thermal generation at mine sites for reliability purposes, is widespread as reliability significantly contributes to costs and safety at a mine site. This other market for self-generating mines is beyond the scope of this study.

These findings are consistent with figures for off-grid mines reported through engagement with mining sector end users. The electrical demand for a representative off-grid mine was reported to be between 2-50 MWe, and respondents noted a growing need for power due to new electrification practices at mine sites or additional processing that is being explored. The demand for thermal energy at these mine sites was reported to be less than 15 MWth, representing only low-grade heat applications such as building heat. Finally, all respondents with off-grid mines noted a typical lifetime of 10-20 years for these mines, with some notable exceptions of off-grid mines with very long operating lives.

Prevalence of remote mining

Off-grid mines that generate their electricity on site represent a small subset of the global mining activity, with estimates placing off-grid mines at 5% of global mining activity (Hatch, 2016). Off-grid mining is typically found in jurisdictions with large land masses per capita, concentrating the market to select regions of Africa, North and South America, Oceania, and Russia.

The opportunity for SMRs to support the energy transition at off-grid mine sites that self-generate electricity will be evaluated by conducting a market size analysis of existing remote mining operations.

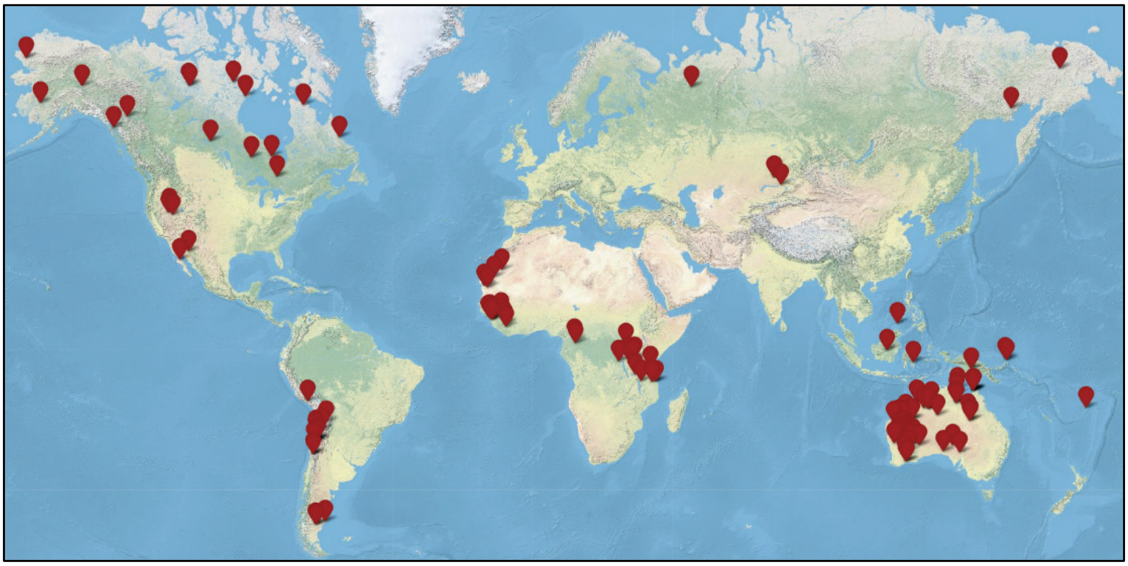
An open database of existing global coal and metal mine production was published by Jasansky et al. in 2023 and will be leveraged in this analysis (Jasansky et al., 2022; Jasansky et al., 2023). This database compiles more than 1 900 public mining company reports from 2000-2021, totalling 1 171 mine sites with production, processing capacities, and geospatial location data. Coal mines were discarded in the subsequent analysis. Metal mining facilities span 80 countries, with Australia, Brazil, and the United States representing the greatest contribution. The database does not include complete global coverage, with notably reduced coverage in regions of Russia and India and very low coverage in China, which is among the largest international producers of many commodities. At the detailed plant level, this database appears to be the most complete open-sourced geospatially referenced resource available at the time of assessment. Notably, this dataset does not include non-metallic mining for industrial applications (such as potash or soda ash mining) or mining activities associated with energy production (such as oil extraction, coal mining, or uranium mining).

To determine which geospatial mine elements were in remote areas, an approximation of the world's predicted electricity grid system was utilised from Arderne et al. (Arderne, 2019; Arderne et al., 2020). This database of medium- and low-voltage electric transmission line data was developed using advanced algorithms on geospatial data. The authors have determined the accuracy of this data to be approximately 75% across validated countries.

Using the available data, a nearest-neighbour algorithm was used to determine the approximate physical distance of each existing mine facility to the nearest electrical transmission line. Each mining facility was ranked according to these distances to determine which mines were the most remote. A minimum distance of 20 kilometres from the predicted electricity grid was used as a threshold to classify a mining facility as a "remote" mine. This distance was verified as an acceptable assumption through mining sector engagement while in practice the actual distance for which it is feasible for a mine to connect to existing infrastructure is dependent on several localised factors. This threshold should therefore be considered an approximate prediction to estimate the number of off-grid mines globally.

Finally, to account for the reduced coverage of the dataset, the remote mine data was supplemented with additional publicly available information on mining operations that self-generate their electricity. Notably, mine sites in Sub-Saharan Africa were manually added to the remote mine database using data from the World Bank Group (Banerjee et al., 2014), where approximately 10% of mining activity is from self-generating mine sites using diesel or HFO.

Figure 3.2: **Existing mines determined to be more than 20 kilometres from an electricity grid or self-generating with diesel as a fuel**



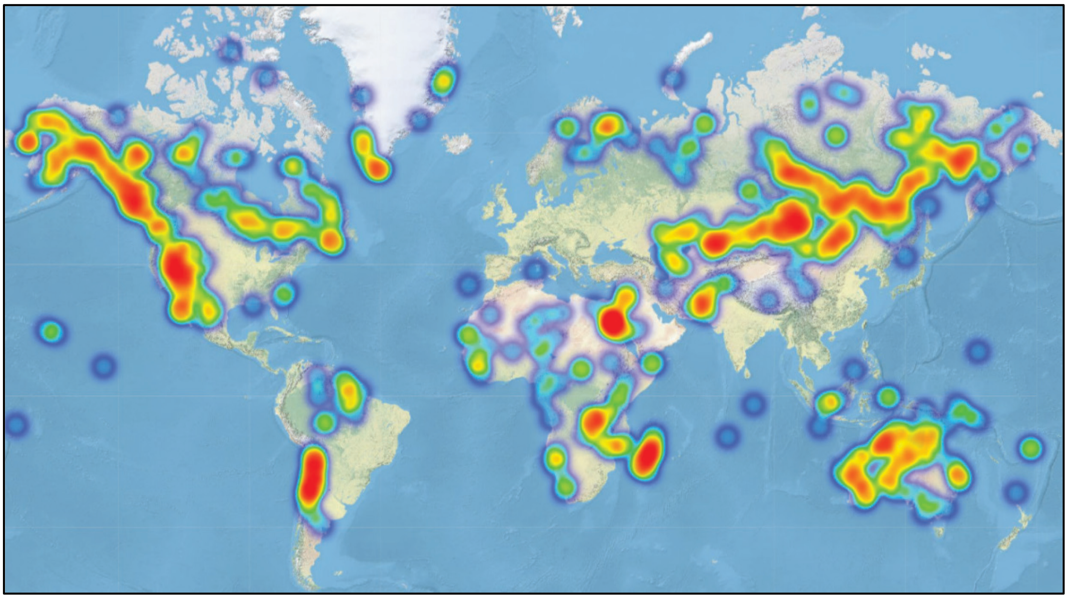
One hundred and thirty metal mining facilities were determined to be more than 20 kilometres from the predicted electricity grid, noting that the data does not represent the complete global mining operations. This includes six remote mines in Asia, twenty-seven in Africa, three in Europe, twenty-three in North America, fifty-seven in Oceania, and fourteen in South America. These remote metal mining facilities represent 5.2% of the mining facilities included in the dataset and are used as a proxy for existing off-grid mines operating globally.

Remote mineral deposits and critical minerals

Mineral deposits that are in remote locations and represent a future opportunity for off-grid mining were also identified. Mineral deposit data is available from open-source data from the US Geological Survey. Two datasets were merged to identify global geospatially referenced mineral deposits. In particular, the 2005 database of known significant mineral deposits was systematically merged with the 2017 dataset on the worldwide distribution of critical minerals (Schulz and Briskey, 2005; Labay et al., 2017; Schulz et al., 2017). The combined data contains 4 946 unique mineral deposits around the world.

Using a similar approach to determine the existing mining operations in remote areas, the predicted electricity grid system from Arderne et al. was used to determine the mineral deposits more than 20 km from the electricity grid. In contrast to the 5% of existing mines operating in remote areas, 15.8% of metal mineral deposits (784 deposits) were determined to be remote. This suggests that proximity to the electricity grid is a key driver in the feasibility of a mining project. The distribution of these remote mineral deposits is available in Figure 3.3.

Figure 3.3: **Remote mineral deposits determined to be more than 20 kilometres from an electricity grid**



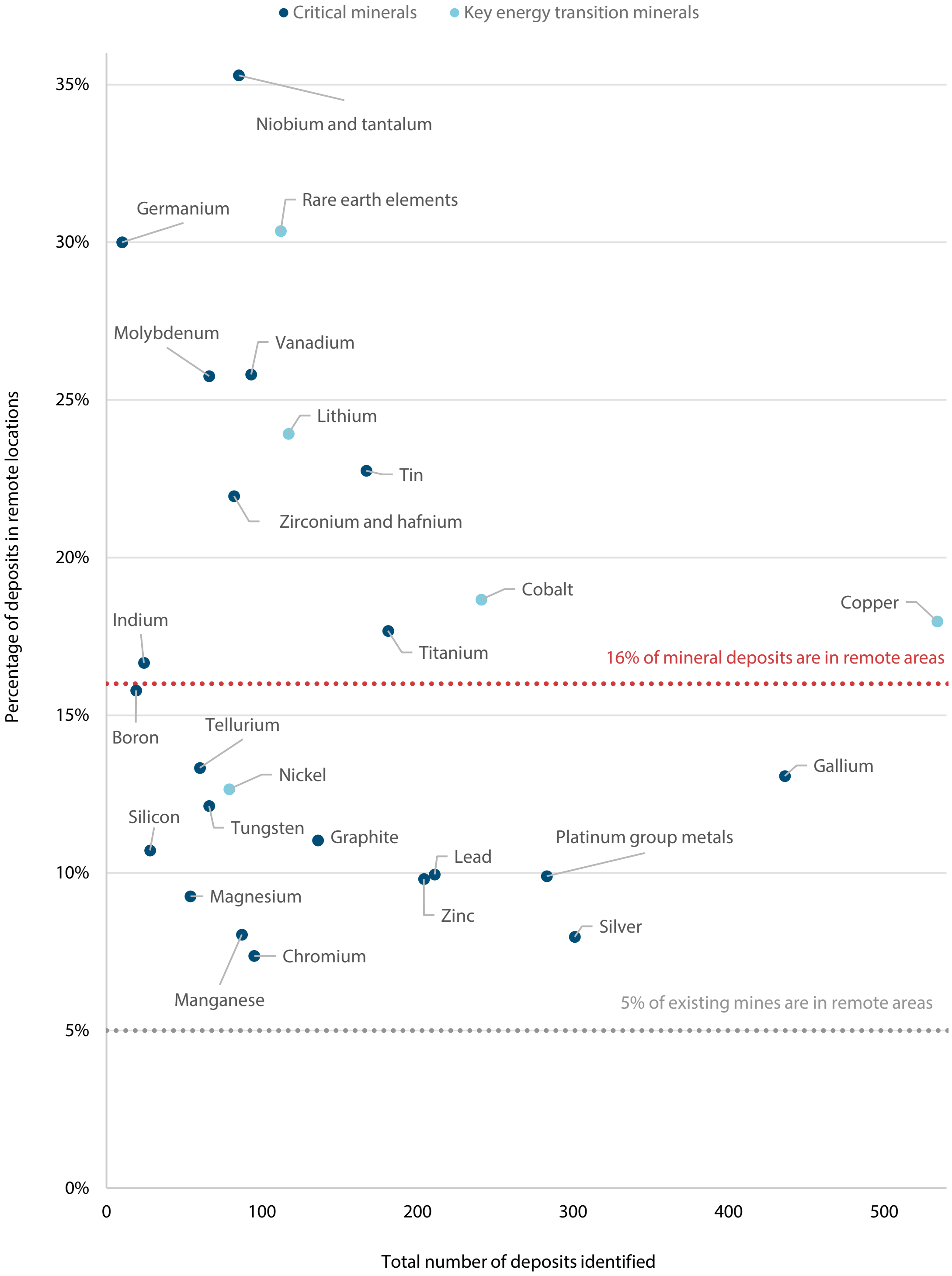
Some jurisdictions have a higher proportion of mineral deposits in remote areas, which could incentivise efforts to make off-grid mining more feasible. Some 43% of mineral deposits were determined to be more than 20 kilometres from the electricity grid in Oceania, 23% in South America, 17% were identified in Europe, including Russia, 16% in North America, 11% in Asia, and 10% in Africa.

The study of remote mineral deposits was expanded to consider specific critical minerals identified by the International Energy Agency (IEA) (IEA, 2024). The IEA *Critical Minerals Market Review 2023* has noted significant investment and demand for critical mineral production in recent years and found the cost and success of the clean energy transition to be heavily influenced by the availability of critical minerals (IEA, 2023). The IEA Critical Minerals Data Explorer provides demand projections for 37 different critical minerals that are included in technology scenarios in support of the clean energy transition. Among these, the following key energy transition minerals are identified, which have observed heightened demand and rising prices over the past five years: copper, lithium, nickel, cobalt, and rare earth elements (IEA, 2024).

NEA analysis of remote mineral deposits was used to explore the abundance and accessibility of the critical minerals identified by the IEA. While on aggregate the trends associated with critical minerals are aligned with broader significant mineral deposits, some specific critical mineral deposits were found more commonly located in remote areas. Figure 3.4 shows the number of mineral deposits identified for each critical mineral and the corresponding percentage that was found to be more than 20 km from the nearest electricity grid. Notably, the five key energy transition minerals appear to be systematically located in remote areas in the highest proportions. Overall, 30% of rare earth element mineral deposits were found in remote areas, along with 24% of lithium deposits, 19% of cobalt deposits, 18% of copper deposits, and 13% of nickel deposits.

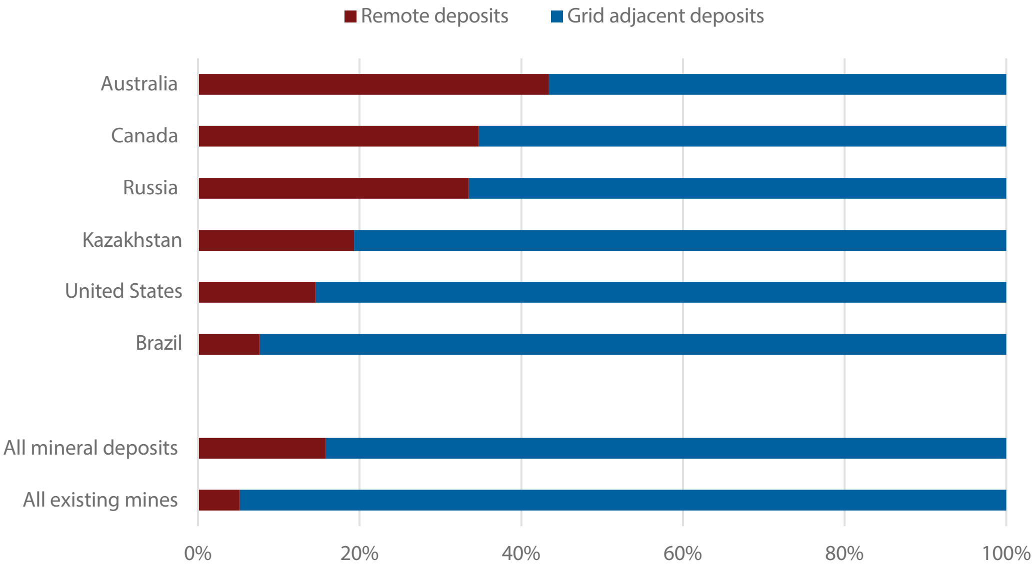
Some countries also have a higher portion of their critical mineral deposits in remote areas. Three countries with remarkably high proportions of their critical minerals in remote areas include Australia at 43%, Canada at 35%, and Russia at 33%. This implies that these countries may benefit the most if remote mining becomes more economical. Given the strong policy environment in Canada for nuclear energy compared to Australia, Canada appears to be uniquely well-positioned to benefit from SMRs in remote mining environments for the production of critical minerals.

Figure 3.4: **The determined accessibility of global critical mineral deposits including key energy transition minerals**



Note: Key energy transition minerals have been identified by the International Energy Agency in the 2023 *Critical Minerals Market Review*. They are rare earth elements, lithium, cobalt, copper, and nickel.

Figure 3.5: **Relative distribution of mineral deposits that are less than, and more than, 20 kilometres from an electricity grid representing grid-adjacent and remote deposits, respectively, among select countries**



Comparison of costs of diesel in remote areas and SMRs

SMRs are not commercially available, and the costs associated with deploying SMRs at an off-grid mine site are predicted, but presently unconfirmed. Expenses related to generating electricity by micro-SMRs have been predicted across a wide range of values in recent years. Expected costs will continue to be refined through successful demonstration projects of micro-SMRs within the next 5-10 years.

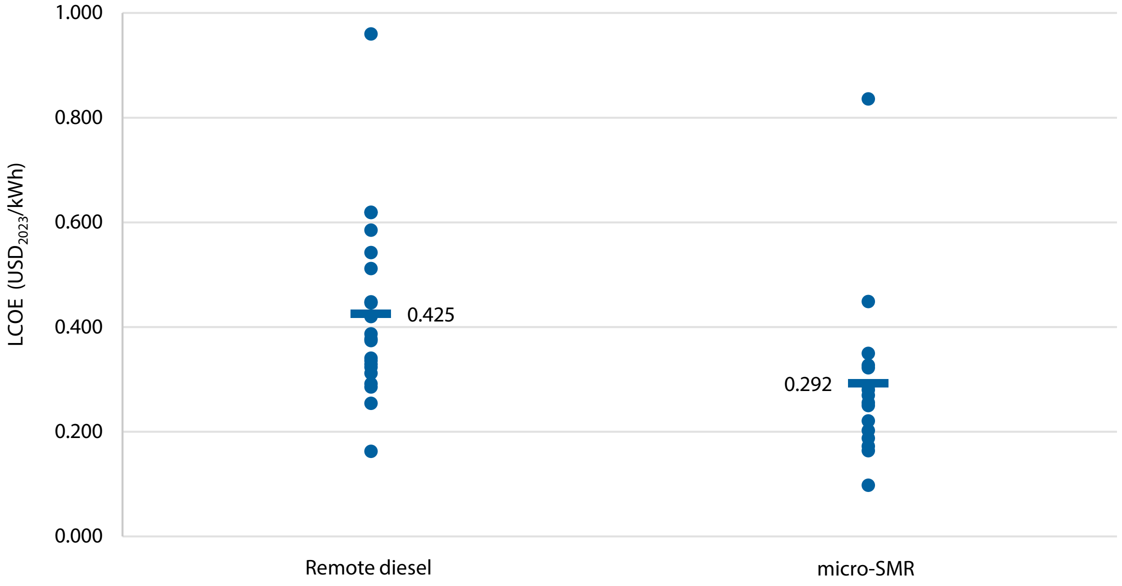
A common and simple metric in electricity system modelling is the levelised cost of generating electricity (LCOE), which provides a straightforward means to compare the plant-level costs of generation technologies (IEA/NEA, 2020). LCOE comparisons are limited as they do not include consideration of system-level costs. All energy systems that include plans for wind and solar generation would benefit from system costs analysis that also accounts for intraday fluctuations in the demand profile (NEA, 2022). Additional considerations that are not captured in LCOE comparisons extend to social, environmental, economic, and sustainability benefits. Nevertheless, for comparison of the estimated costs of micro-SMRs to diesel at an off-grid mine over the lifetime and decommissioning of the energy assets, LCOE is sufficient to the extent that it demonstrates the plant-level economic competitiveness of this option compared to diesel.

Estimated LCOE values for micro-SMRs have been estimated at a range of values spanning nearly a decade. The Nuclear Energy Institute estimated the LCOE for a first-of-a-kind 5 MWe micro-SMR to be between USD 0.14/kWh and USD 0.41/kWh in the United States, and the costs reduced to USD 0.09/kWh-0.33/kWh for subsequent units (NEI, 2019). LCOE costs are also largely dependent on site-specific conditions and regulatory environments. In spite of the range of estimated LCOE values for micro-SMRs, some data suggests that micro-SMRs may be competitive with existing energy solutions at off-grid mine sites once they become commercially available.

Accurate values for the levelised cost of diesel in remote areas are available and vary significantly depending on the jurisdiction and requirements for transportation and storage. A typical LCOE range for northern and remote regions of Canada is reported to be USD 0.18/kWh-0.60/kWh (CBOC, 2020). In off-grid regions of central Australia, this range is estimated to be USD 0.24/kWh to USD 0.45/kWh, excluding capital costs (AECOM, 2014). This range increases from USD 0.50/kWh to over USD 1.00/kWh for isolated communities in Alaska and the United States (DOE, 2019), and can decrease to USD 0.29/kWh for self-generating mine sites in Sub-Saharan Africa (Banerjee et al., 2014).

A meta-analysis of diesel usage in remote areas is conducted to compare the range of predicted values for micro-SMR costs. LCOE values for diesel from remote regions of Alaska in the United States, Australia, Canada, and areas of Sub-Saharan Africa are used in the meta-analysis. Predicted LCOE values were sourced for micro-SMRs in the range of 3 to 20 MW and include estimates for both first-of-a-kind and nth-of-a-kind units under a range of assumptions. Costs were converted to 2023 USD, and average LCOE values are determined to be USD 0.425/kWh for diesel in remote areas and USD 0.292/kWh for predicted micro-SMRs. The corresponding sample sizes are 21 and 16; the median values are USD 0.377/kWh and USD 0.263/kWh, respectively.

Figure 3.6: **Meta-analysis of levelised cost of electricity from diesel in remote areas and predicted costs of micro-SMRs**

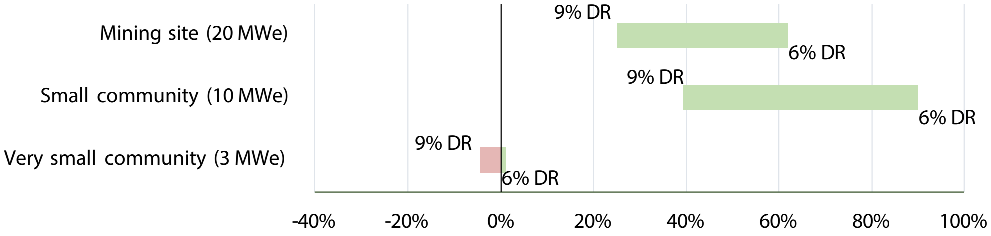


Source: Aggregate date from CBOC, 2020; Hatch, 2016; AECOM, 2014; Canadian SMR Roadmap, 2018; EFWG. 2018; Caron et al., 2021; Shropshire, Black and Araujo, 2021; NEI, 2019; Banerjee et al., 2014; Votteler and Brent, 2016; DOE, 2019; SRG, 2018; Sam-Aggrey, 2016; WPB, 2021.

This analysis suggests a potential cost advantage of 31% when introducing micro-SMRs into existing off-grid mining operations. Due to the limitations of LCOE analysis, this finding does not reflect the additional value that SMRs may introduce such as avoiding GHG emissions, including a plan for decommissioning and waste management, and reducing the volatility of a mine's operating costs. The competitiveness of SMRs will also be impacted by policies that impact fossil fuel combustion, such as a carbon tax.

This finding is consistent with the Canadian SMR Roadmap, which modelled a 20 MWe SMR for use in the mining sector and determined an estimated cost advantage of 20 to 60% over diesel on an LCOE basis, where the cost of capital varied from a 6% to a 9% discount rate (Canadian SMR Roadmap, 2018). The findings from this earlier work are available in Figure 3.7, which illustrates the cost competitiveness of SMRs against diesel generation, and highlights the sensitivity to discount rates (DR) for three different applications of various sizes.

Figure 3.7: **Cost advantage of SMRs over diesel consumption in Canada**



Note: Differences are expressed as a percentage of the LCOE of diesel in three remote applications shown for 6% and 9% discount rates (DR).

Source: Canadian SMR Roadmap, 2018.

The LCOE comparison concluded in this study may support system cost modelling performed in North America and Australia, including from Canadian Nuclear Laboratories (CNL) in Canada, MIT in the United States, and the University of Queensland in Australia. CNL modelled a representative open-pit remote diamond mine in Canada and identified an opportunity to reduce GHG emissions by nearly 95% by introducing SMRs and other clean energy options instead of diesel generation without significantly increasing overall system costs (Bayomy et al., 2023). MIT similarly modelled a representative remote community and mine site and found that the ability to recover heat from a microreactor to meet the associated thermal demand is a valuable characteristic that supports the economic viability of deploying microreactors to support the decarbonisation of these applications (Macdonald and Parsons, 2021). The University of Queensland omitted SMRs in their assessment but identified an optimal hybrid energy solution to power communities neighbouring mine sites and found that the inclusion of concentrated solar, photovoltaic, and battery storage to existing diesel generation reduces overall generation costs on an LCOE basis without considering additional costs associated with carbon emissions (Balaji and Gurgenci, 2019).

Costs associated with building electrical transmission infrastructure

Instead of self-generating electricity at a mine site, another option for off-grid mining operations to reduce their reliance on fossil fuels is to electrify their operations and develop infrastructure in co-operation with the electrical grid operators and other stakeholders to connect the mine to a regional grid. Developing electricity grid infrastructure significantly benefits surrounding communities and is considered a substantial socio-economic benefit of developing new mining operations in remote areas with isolated communities (NEA, 2023). The development of new transmission is an important consideration in the context of SMRs as it represents an alternative capital-intensive option for mining companies seeking to maximise benefits and minimise project costs. Capital costs associated with transmission infrastructure may therefore represent a possible upper limit on the acceptable upfront capital costs of SMRs.

For mining projects, infrastructure developments such as constructing and maintaining transmission lines have faced challenges in recent years, which depend on the project's footprint and the diverse terrain. Securing land claims for transmission lines is a complex process involving rights and claims from local communities, indigenous groups, or governments. In addition, building distribution networks also create ongoing operating expenditures associated with maintaining the infrastructure asset.

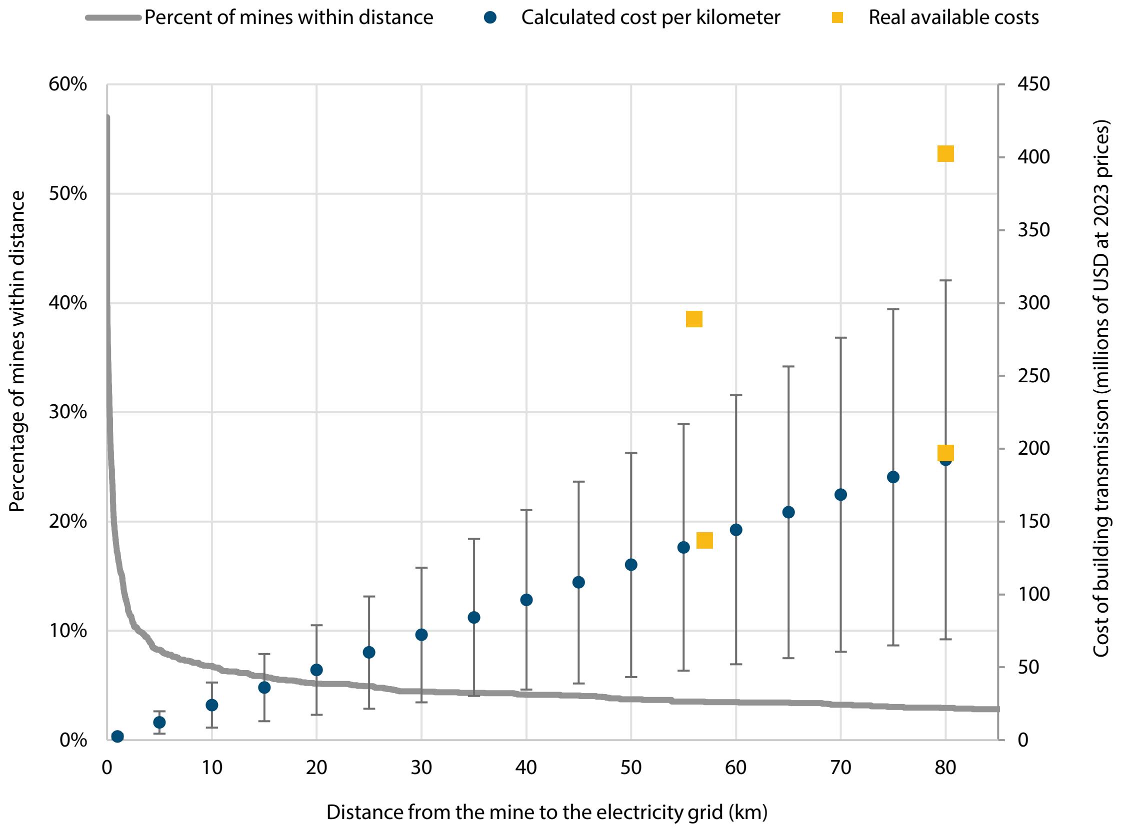
Lastly, regional grids are under stress from new projected demand and are facing decarbonisation challenges in parallel to industrial decarbonisation efforts. Adding demand to regional grids has implications that can impact the reliability and costs of other electricity consumers, especially if the electrical demand profile is volatile or changes seasonally. In addition to increased electricity supply to satisfy new customers connecting to an electricity grid, transmission upgrades are typically required with independent costs and timelines, especially in remote regions.

Building infrastructure in remote areas is a capital-intensive project, and the costs have increased in recent years. For the proposed Brucejack gold mine in British Columbia, Canada, Pretium Resources reported in 2017 that USD 108.8 million had been allocated in an updated capital cost estimate to complete the construction of a 57-kilometre transmission line that is required for the commissioning of the mine. This represented in 2017 USD 1.909 million/km in capital costs for transmission lines in remote regions (Pretivm, 2017). Adjusted for inflation, this is equivalent to about USD 2.38 million/km of transmission line infrastructure as of 2023.

An analysis of actual as well as estimated costs of building transmission lines in remote areas was conducted, using examples similar to the Brucejack gold mine. The capital cost of building transmission was identified to be between USD 1.3 and 5.2 million/km as of 2023 (Morris, 2015; Pretivm, 2017; de Loisy, 2019; Blair et al., 2019; AEMO, 2021) This illustrates the significant costs associated with developing transmission in remote areas to connect remote mines to an electricity grid. Using the median value of USD 2.4 million/km, a hypothetical mine 20 km from a distribution network would require USD 48.1 million in initial upfront capital to connect to the electricity grid.

Figure 3.8 compares these normalised costs to data on the proximity of existing mine sites to the nearest electricity grid, as described previously. The relationship of cost per kilometre was determined using normalised data in the literature, and real available costs are plotted where available. This figure demonstrates that a small set of mining companies operating in remote areas may be required to pay significant penalties to connect to a nearby regional electricity grid if they do not self-generate their electricity on-site.

Figure 3.8: **Mining facility proximity to the electricity grid and corresponding costs associated with building transmission line infrastructure**



The evaluation of transmission line capital costs also suggests an increasing trend in recent years. While the actual rate of increase for the average cost of transmission per unit of distance is difficult to quantify due to limited available data, a 40% increase was noted between 2015 and 2022 when adjusted for inflation, which is consistent with estimates of increasing renewable energy infrastructure costs globally over the same period.

Market size assessment for off-grid mining

Using the determined characteristic off-grid mine profile and the 130 remote mines identified previously, a conservative theoretical estimate of 2.08 GWe of electricity is currently generated by diesel or HFO at off-grid mine sites with corresponding transportation and fuel costs. This represents an immediate opportunity for clean energy alternatives at existing brownfield off-grid mining operations. This predicted market size is consistent with a 2016 estimate from Hatch, which estimates that micro-SMRs could serve an immediate global market size of 2.7 GWe of brownfield generating capacity (Hatch, 2016).

Among the identified countries with remote mining operations, the only OECD member countries with nuclear energy in the mix with no plans to phase out nuclear energy are Canada and the United States. This specifies an immediate market opportunity of 288 MWe of thermal generation in North America to be replaced at existing brownfield off-grid mine sites.

Given the increased demand for major minerals, the expected future market for greenfield deployment of micro-SMRs to support off-grid mining operations could be significant. If the proportion of mines that are developed in remote areas remains consistent at 5%, existing projections of a 6-fold increase in major metal production suggest that the theoretical total global demand for off-grid mining operations will be 12.5 GWe by 2050 (Banerjee et al., 2014). If generating electricity at an off-grid mine site from an SMR proves economical, the market opportunity may be much greater due to the significant demand for critical minerals, geopolitics associated with critical mineral supply chain security, and the corresponding prevalence of critical minerals found in remote regions, as discussed previously.

These findings are consistent with a recent global market size estimate for micro-SMRs by Idaho National Laboratory (INL) for a range of applications, including remote mining. INL estimates an immediate market size of 400 MWe to 900 MWe by 2030 and an eventual market size of 27 to 119 GWe by 2050 (Shropshire, Black and Araujo, 2021). This is consistent with this immediate market prediction for micro-SMRs of 288 MWe for off-grid mining at brownfield sites and a market opportunity exceeding 12.5 GWe by 2050 for off-grid mining broadly.

Finally, it is clear that a number of additional market factors will contribute to the market size beyond what is quantifiable as the existing potential for isolated mines and deposits.

Due to various constraints, off-grid mining operations typically engage in minimal on-site processing. However, there is a significant and diverse demand for increased processing capabilities. The availability and reliability of on-site power influence the size of a mine. Providing additional reliable power could stimulate new markets for this energy. Such a development would enable more extensive on-site processing, allowing mines to capture a more significant portion of the value chain. This aspect is particularly relevant in the current global context, where countries increasingly seek to reduce market centralisation and promote regional supply chain development, particularly in extracting and processing critical minerals.

Fringe-of-grid mines are characterised by connecting to the electrical grid while maintaining self-generation electricity capabilities (AECOM, 2014). This practice is widespread in the mining sector for several reasons. First, the consistency and reliability of electricity supply are crucial, especially in higher-risk environments such as underground mines where power failure can be life-threatening. For these mines, reliable electricity may be required on-site to enable continuous ventilation and access to the surface to ensure the safety of workers. Additionally, specific equipment, such as ball mills used for processing, may require dedicated self-generation to meet their substantial electricity demands and mitigate risks associated with power loss, which could result in equipment damage or operational downtime. Through engagement with mining sector end users, more than 3/4 of mining companies with grid-connected operations generated additional electricity on-site to ensure a supply of reliable and sufficient power. The additional power is reportedly generated primarily by natural gas or diesel.

Another aspect is using waste heat from diesel generators or other generation methods for small-scale thermal requirements at the mine, such as district heating for on-site buildings, which is currently a common practice for mining operations. This aspect of self-generation contributes to the market potential for SMRs in the mining sector as a replacement for diesel compared to alternatives that produce electricity directly.

In addition to the anticipated increase in on-site processing, mine expansions represent another aspect of incentivised demand. Expansions are particularly relevant in critical minerals, which can often be produced in conjunction with other primary minerals. The expected growth in demand for these minerals could significantly influence the energy requirements at mining sites, thus creating a market for more efficient and sustainable power solutions. These factors must be considered in current operational planning and future technical considerations for mining operations.

Apart from mining, various other remote industrial applications require reliable, energy-dense, and low-carbon power solutions. These sectors can benefit from the technological advancements in SMRs initially developed for mining applications, which can contribute to an expanded market demand beyond the mining sector. This includes the use of SMRs to power emerging opportunities in remote areas for dedicated clean energy production, such as remote communities, military bases, merchant shipping, applications in space, and isolated industrial processes, such as remote shale oil production. Future work is required to evaluate the role of SMRs in these complementary sectors.

Key findings and recommendations

Given the demand for minerals to develop and construct clean energy technologies, it is essential to reduce emissions across the mining sector to ensure a sustainable clean energy transition. There are particular challenges associated with decarbonising mines that are off-grid, as there are limited options available to generate reliable energy on-site in a remote area. Off-grid mining is expensive, primarily due to the high costs associated with generating electricity in remote areas. As a result, markets are signalling a demand for SMRs to support the decarbonisation of off-grid mining, which broadly reflects access to some essential critical minerals.

Due to the high costs, small off-grid mines represented a small percentage of the global mining activity in 2024 and reflect an opportunity for micro-SMRs. While 15.8% of mineral deposits were found in remote areas, only 5% of existing mining operations operate in remote areas. This suggests that mines are much more commonly developed in regions with access to an electricity grid, as energy availability is a significant driver for mine feasibility.

A study of 51 remote mine sites currently reliant on diesel or HFO determined a representative installed thermal capacity to be 16.0 MWe and a representative project lifetime of 16 years. Mean values are 31.3 MWe and 20.2 years, respectively. Although these figures do not take into consideration additional future demand, including from nearby communities or off-takers that may benefit from additional clean energy generated on-site, it is believed that micro-SMRs may be well-suited in such contexts. SMRs are not commercially available, and the costs associated with deploying micro-SMR at a mine site are unknown. Predicted costs for micro-SMRs were found to be competitive for off-grid mining applications currently reliant on diesel, offering a 31% cost advantage over diesel usage in remote environments of Africa, Australia, and North America on an LCOE basis. Due to the wide range of predicted costs associated with deploying first-of-a-kind and nth-of-a-kind micro-SMRs, the uncertainty in this estimate is significant.

Some 130 mining facilities have been identified that operate more than 20 kilometres from the predicted electricity grid, representing an opportunity for micro-SMRs at existing brownfield off-grid mining operations. A theoretical 2.08 GWe of electricity is currently generated by diesel or HFO, primarily concentrated in Australia, Canada, Chile, Guinea, and the United States.

Among these, Canada and the United States are the only OECD countries with policies in place to expand nuclear energy generation. This represents an immediate market opportunity in North America of 288 MWe of thermal generation to be replaced at off-grid mine sites.

Using broad mineral demand projections, the future greenfield market for off-grid mining is determined to be 12.5 GWe by 2050, assuming that off-grid mines are developed in the same proportion of 5% of global mining activity.

NEA analysis projects a growing need for off-grid mining due to increased demand for critical minerals essential to technologies required for the clean energy transition. Significant demand growth is expected for critical minerals. The IEA is calling for a 7x increase in critical mineral production for some CMs by 2030.

Critical minerals are more commonly found in remote areas compared to other metal commodities. The NEA found that 16% of critical mineral deposits globally are located more than 20 km from the nearest electricity grid, significantly higher than the benchmark of 5% of existing mines in remote areas. Some critical minerals, such as rare earth elements, niobium, lithium, cobalt, and copper, are more commonly found in these remote areas.

If off-grid mining becomes more economical, it could help to reduce the cost of the clean energy transition as it will enable greater access to critical minerals necessary for a wide range of clean energy technologies such as solar panels and batteries. It is essential that off-grid mining becomes more feasible to support a secure supply chain in support of the clean energy transition.

Micro-SMRs have been identified as a potential solution for off-grid mining as predicted costs appear to be competitive with existing diesel generation in remote areas. This report has also demonstrated the significant capital costs of building transmission infrastructure to serve remote areas.

Among NEA member countries, off-grid mining environments in Canada appear well-positioned to benefit from micro-SMRs. There is a favourable policy environment in Canada for SMRs; there is a relatively large number of existing off-grid mining operations that could benefit from deploying SMRs at brownfield operations, and there is a high proportion of critical mineral deposits in remote areas which could be developed into new mines in the future.

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Conclusions and policy recommendations

The global mining market accounts for more than USD 2 trillion of economic activity and is in a period of rapid growth in response to the demand for raw material needed for the clean energy transition. Among the 40 largest publicly traded mining companies globally, those with public emission reduction targets account for a combined market capitalisation exceeding USD 1 trillion, demonstrating the scale of the transition. Countries are also implementing policies to achieve net zero emissions in industrial sectors, and to ensure resiliency and domestic security across the mining value chain.

This report responds to the growing interest in SMRs globally as an option for low-carbon heat and electricity to support the decarbonisation of the mining sector and works to inform policymakers on the drivers, characteristics and projected timelines for the deployment of SMRs for mining, mainly focusing on smaller off-grid mining applications as an initial market. The findings are grounded in an assessment of the energy requirements, environmental impacts and market dynamics within the mining industry, particularly concerning the adoption of clean energy technologies.

This report presents conclusions about the size and geographic distribution of a global market for SMRs for mining. It also describes technical, operational, and business requirements for SMRs at mine sites, which vary considerably based on the commodity, the mine type, and localised features. The latter refines the former. The global market is significant but heterogeneous. This analysis and conclusions were informed by quantitative analysis of global mining data sets, complemented by extensive direct engagement with mining sector stakeholders to understand the variations of mine-site requirements.

Quantitative and qualitative analysis by NEA reveal that there is a distinct opportunity to use SMRs to satisfy the large power requirements at large mine sites that typically feature on-site processing, with evidence of this opportunity in Poland and the United States. In Poland, the KGHM mining company is working to deploy more than 400 MWe of SMRs to power their copper and silver mining operations by 2029. In the United States, Tata Chemicals Soda Ash Partners is working to evaluate the role of SMRs for their operations in Wyoming to supplement existing power at their soda ash mining and processing facility and to support the company's goal to reduce emissions in the near term. Including an SMR at these sites is expected to change how energy is used at the mine site, and may incentivise new energy demand, or the improved utilisation of thermal energy in alternate mining processes.

This report also focuses on market prospects for micro-SMRs for their deployment in remote or off-grid mining settings, which typically rely on diesel or heavy fuel oil (HFO) to self-generate electricity on-site. Currently there are projects underway in Russia to adopt micro-SMRs for remote mining applications, including for the Baimskaya copper mine and processing facility, the Seligdar Gold Mine, and a new mine at the Sovinoye gold deposit which will also provide power for nearby communities. There is also significant interest in North America, with studies focusing on the opportunity to use micro-SMRs to replace diesel consumption in remote regions of Canada and in Alaska.

Considerations for SMR adoption in the mining sector

To examine technical, business and operational requirements for stakeholders in the mining sector, engagement with industry end users was sought through structured interviews, a survey and the newly created group of NEA SMR Advisors for Industrial Applications (SMIA). Mining sector participants provided valuable feedback on their specific energy demand and technical needs, expressing their concerns and opportunities regarding adopting SMRs.

This engagement, supported by available literature, suggests that there is significant variation among the needs of mining companies across the sector, which for a specific mine depend on the commodity, the mining techniques used, and region-specific considerations. There are therefore a range of environmental, security, economic and strategic considerations when considering SMRs for mining applications.

Environmental considerations

ESG performance in response to expectations from investors and the public is the primary driver for mining companies to consider SMRs as a technical solution for their operations. Nearly all mining sector representatives engaged through the development of this study reported that their companies have targets to achieve net zero carbon-equivalent emissions by 2050, or earlier.

Among ESG considerations, emission reductions across all operations is presently the primary driver among energy-related decisions. Emission-intensive activities includes both electricity production, as well as activities that are more difficult to decarbonise such as high-temperature processes and the use of liquid fuels in mining equipment and haulage vehicles. Notably, off-grid mining faces significant challenges in meeting ESG commitments due elevated operating and construction costs.

Beyond emissions reduction, remediation issues and other environmental concerns in the mining sector are also impacted by the availability and cost of energy at the mine site. The opportunity to adopt environmental best practices in the mining sector is therefore closely linked with the available energy at a mine. A mining company’s energy decisions are essential factors to achieving targets related to environmental, social, and governance performance.

Security and resilience of supply considerations

A reliable and predictable supply of energy is critical to sustain continuous operations of a mine. While the loss or reduction of available power has a direct impact on productivity and operating costs, there are other significant concerns that relate to the safety of both equipment and personnel. Expensive mining equipment can become damaged with a sudden loss or reduction of available power. Constant electricity is also required to ensure the safety of workers in underground mines that need electricity for both underground air ventilation and for hoisting equipment and personnel in and out of the mine.

Energy security was found to be a significant factor in determining the feasibility of a mining project. Using the approximation of mine elements in remote areas that was introduced in Chapter 3, 15.8% of metal mineral deposits were determined to be more than 20 kilometres from the electricity grid, while only 5% of existing mines were similarly found to be more than 20 kilometres from the grid. This implies that the proximity of a mine site to the grid as historically been an important decision variable for developing viable mining projects, which was validated during end user engagement.

For off-grid mines that require liquid fossil fuels such as diesel or HFO to be transported to site to sustain operations, the logistics and transportation costs are a particular driver for mining companies considering micro-SMRs as part of their operations. This is especially true for very remote mines, where fuel and other supplies are transported to site on a seasonal basis.

A universal solution for power in the mining sector is not possible due to the wide variation in mining sector requirements. SMRs appear to be an appropriate technology option in many cases given the requirements for firm power to maximise revenues and ensure operational safety is maintained. Previous work suggests that there are risks associated with the alignment of the total power demand and lifetime of a mine with the power output and lifetime of an SMR, however these risks as not perceived as a significant barrier to SMR adoption the mining sector, as energy availability has a direct influence on the scale and growth potential of a mine.

Economic considerations

Assuming that environmental and energy reliability requirements are addressed, mining sector stakeholders reported that the economic competitiveness of SMRs among other clean energy options will primarily drive investment decisions. For SMRs, the high initial costs of constructing and deploying an SMR pose a significant barrier, while the long-term predictability of supply offers an advantage. Financial incentives and support from governments may help mitigate risk associated with the capital-intensive process of decarbonising mining.

A competitive advantage of SMRs is their ability to produce heat without the consumption of fossil fuels and the associated CO_2 emissions. Currently, the use of thermal energy in mining is limited to low-grade applications such as district heating. However, there is potential to adapt existing processes to utilise high-quality thermal energy, which could be economically competitive and improve environmental performance. This highlights the importance of a system analysis approach using plant-level energy demand and specific process requirements and considering a range of clean energy technologies.

Off-grid mines operating in remote areas typically have characteristically high costs regardless of the jurisdiction. While the actual costs of micro-SMRs remain unknown at present, micro-SMRs were estimated to potentially be a cost-effective alternative to traditional diesel generators in remote mining operations on a levelised cost of electricity (LCOE) basis. In particular, an estimated 31% cost reduction was identified when introducing micro-SMRs into existing remote mining operations to replace diesel. This was compared to the capital costs associated with building transmission to connect remote mines with a regional electricity grid, which was found to be approximately USD 2.4 million per kilometre of transmission built.

Broadly, there is very little reliable data available to mining sector end users to make an informed business decision on the potential applicability of SMRs to their operations. Initial demonstrations of first-of-a-kind SMR technologies suitable for the mining sector are expected to provide critical data that will benefit energy decision making in the mining sector.

Strategic considerations

At a mine, energy infrastructure is a strategic asset for the mining company, which influences operational decisions, public acceptance and a mine’s ability to attract financing.

Mining companies noted that predictability of an energy supply enables companies to make important business decisions, especially related to innovation or justifying investment to expand an existing mine. For off-grid mines that routinely transport large quantities of diesel or HFO to a remote facility, the fluctuating price of fuel can create uncertainty and additional project risk. In these cases, a micro-SMR that features long refuelling timelines may be of strategic importance for sustained operations.

Energy decisions also impact public perception and the ability to attract financing and investment into a project, which is critical to the longevity of existing mines and the development of new mines. The decision to invest in energy infrastructure is expected to positively contribute to the public acceptance of a mine project, especially in remote areas where these investments may directly increase access to energy for neighbouring communities. Long-term operational predictability also helps communications with the local public, which may rely on the mine for its livelihood.

Finally, a mine’s energy decision should not create a distraction to the core business. Companies noted that they are exploring business models for energy options that will allow them to focus on their core business of mining. For SMRs, many are exploring second party owner-operator models, where a different organisation may operate the SMR and sell heat and power to the mine through power purchase agreements.

Opportunity and benefits to SMR adoption

Engagement with mining sector stakeholders revealed that there exists clear interest for SMRs to support the decarbonisation of the mining sector. Reliable, firm, and predictable heat and electricity from an SMR is expected to benefit large mining operations in jurisdictions with favourable policy environments. This opportunity will continue to evolve as energy demand increases from the adoption of alternative processes that rely on electrification, hydrogen or high-quality thermal energy.

This study identifies an opportunity for micro-SMRs to provide power to off-grid mines, where construction and operating costs are systematically elevated when compared to grid-connected mines. A literature review of existing and planned off-grid mines identified a median power requirement of 16.0 MWe and a median lifetime of 16 years, which is consistent with end-user engagement. While these values represent a smaller characteristic of off-grid mines, the lifetime and energy demand of a mine is dynamic and is directly influenced by energy availability. The inclusion of a micro-SMR at an off-grid mine and the energy requirements of nearby communities may therefore generate additional new demand.

The quantitative market analysis included in Chapter 3 evaluates the existing and potential markets for micro-SMRs in off-grid mining applications, which was found to represent approximately 5% of global mining activity concentrated in the regions of Australia, Canada, Chile, Guinea, and the United States. A current market exceeding 2 GWe was identified for off-grid brownfield mining operations reliant on diesel and heavy fuel oil, which could adopt SMR technology as a retrofit solution. Among the countries with significant remote mining operations, Canada and the United States are the only OECD member countries with nuclear energy in the mix with no plans to phase out nuclear energy. This represents an immediate market opportunity of 288 MWe of cogeneration assets in North America to be replaced at existing brownfield remote mine sites.

The study also anticipates a significant market for new greenfield mining projects in remote areas, which includes a dedicated analysis for critical mineral deposits. Australia (43%), Canada (35%) and Russia (33%) have an uncommonly high proportion of mineral deposits in remote areas. Given this opportunity and the strong policy environment for nuclear energy, remote mines in Canada appear to be well-positioned to benefit from the deployment of SMRs, including for the production of critical minerals.

For critical minerals, the relative proportion of mineral deposits found in remote areas is consistent with the broader average for all major metals and minerals. Some critical minerals prove to be an exception, including the five key energy transition minerals identified by the IEA as critical for achieving global climate objectives. These key energy transition minerals are more commonly located in remote areas, with 30% of rare earth element mineral deposits in remote areas, 24% of lithium deposits, 19% of cobalt deposits, 18% of copper deposits, and 13% of nickel deposits. Enhancing the feasibility of remote mining may be crucial for securing a stable supply chain for critical minerals required for the clean energy transition.

Challenges to SMR adoption

Several challenges related to SMRs were identified by mining sector stakeholders, including a need for predictable policy support, public acceptance and reliable information on the available technology options. The primary concerns among energy end users in the mining sector are the regulatory and permitting timelines and uncertainty about costs associated with deploying SMRs.

Mining companies that may benefit from SMRs may have operations in jurisdictions that currently do not have policy support for nuclear energy, such as in Australia or in regions of Africa. Policy support for nuclear energy and a streamlined regulatory process would reduce risks for mining companies.

Cost uncertainty is a significant challenge for mining companies that are considering SMRs, as the costs of constructing and deploying SMRs are not presently refined. While there are estimates for SMR costs, including micro-SMRs, there is a need for detailed cost data for SMRs coming to market. Initial demonstrations of first-of-a-kind SMRs will be essential to increase confidence among mining sector end users.

Timelines to commercialisation are also perceived as a barrier to adoption. Many mining companies have targets to reduce direct emissions from their operations by 2030, and SMRs are not expected to be commercially available in time to meaningfully support these immediate targets. SMRs are therefore expected to primarily contribute to 2040 and 2050 ESG targets in the mining sector.

Concerns also extend to the robustness of the nuclear supply chain, including material requirements and workforce training, as well as the necessity for public engagement and community acceptance. Public opinion, especially in regions with a history of unsustainable mining operations, adds complexity to project approval in some jurisdictions.

Beyond electricity and thermal energy, high-temperature heat required for mineral processing and liquid fuels for mining vehicles and heavy equipment pose a significant challenge to decarbonise. As these energy requirements are replaced with electrification and other alternatives, the energy profile of a mine site will evolve considerably and further complicating analysis on the suitability of various energy systems.

Recommendations

A significant effort is required to address the range of considerations and concerns identified in this study, especially given the scale and urgency of the clean energy transition within the mining sector and the demand to increase mineral production. In order to capture the opportunity, the following recommendations should be considered.

High-level principles

Building on engagement with mining sector end users, high-level principles to explore the opportunity for SMRs in the mining sector are presented. In general, partnerships and transparent information sharing is essential between mining companies, SMR developers and energy sector stakeholders. This collaboration is key to addressing technical, operational and safety aspects of SMR deployment and will particularly enable mining companies to understand the implications of including an SMR into their existing permitting processes and understand cost implications.

- **Consider system analysis**: Given the complex energy requirements in the mining sector, mining companies are encouraged to conduct site-specific studies and consider alternative processes that may be more suited to clean energy technologies. Including SMRs at a mine site will require collaboration with new partners in the nuclear sector. Mining companies are encouraged to clearly define their energy requirements where possible and work with partners in the nuclear sector to explore potential business models and alternative mining processes.
- **Collaboration**: SMR technology developers, potential operators, governments, regulators and local communities should acknowledge and familiarise themselves with challenges in the mining sector and the potential role of SMRs. SMR vendors should work to articulate the details of their design, and their potential suitability to the range of energy needs at a mine. The nuclear sector should work to leverage first-of-a-kind deployments of SMRs to showcase the potential application in the mining sector and generate cost and operational data that could help inform the opportunity to deploy SMRs commercially.

- **Develop clear policy frameworks**: Government representatives could help enable SMRs in the mining sector by working to create efficient and clear policies to promote SMRs for industrial applications, including for mining in off-grid areas. Countries should work to enable a streamlined permitting process for SMRs in mining and consider how SMRs may be deployed in remote areas without existing experience with nuclear energy.
- **Monitor and share best practices**: The nuclear and mining industries broadly have a role to facilitate knowledge sharing and establish mechanisms for monitoring the performance of SMR implementations in mining and share best practices and lessons learnt across industry.
- **Public engagement**: Communities that would be impacted by changes to a nearby mine site, or from the implementation of SMRs at a mine, should monitor progress and engage with local governments to share their views. Transparent communication from the mining sector on safety, environmental benefits, and economic impacts will also improve public perception and understanding of SMR technology broadly.

Specific recommendations

Taking into consideration the economic opportunity identified for remote mining, the feedback received from mining sector end users through NEA engagement activities and policy frameworks in NEA member countries, the following recommendations are proposed to address the identified gaps.

- **Evaluate process integration**: Mining companies are encouraged to explore integrated energy solutions and alternative processes that may include greater utilisation of thermal energy, and the integration of SMRs with renewables, energy storage and other clean energy technologies. Current processes are optimised for the combustion of fossil fuels and there may be economic and environmental benefits in alternative processes not yet implemented. Mining companies may benefit from engaging with other industries that are exploring alternate processes that utilise thermal energy, such as the chemicals sectors.
- **Sharing first-mover risks**: Public-private partnerships are recommended to share first-mover risks. For example, to reduce project risk associated with the alignment of the lifetime and power requirements of a mine site, grid operators and regional governments could explore off-take agreements for initial SMR deployments for mining, where appropriate. Off-take agreements reduce sizing risk by allowing excess electricity to be provided to the grid instead of being curtailed.
- **Consider system analyses**: Mining companies should consider the costs, opportunities and challenges of various energy options at a system level to ensure energy reliability at a mine site. Systems analysis should be conducted at high temporal resolution to adequately compare costs among energy alternatives. This is especially recommended if a micro-grid powering a mine includes a variety of clean energy sources and storage.
- **SMR demonstration projects**: Nuclear energy stakeholders that are advancing demonstration projects of first-of-a-kind SMRs should involve mining companies and potential operators so they can understand the costs and operational implications associated with operating a nuclear energy asset. Mining companies should consider an SMR demonstration at a mine site so that they can immediately benefit from the technology and resolve global uncertainties surrounding regulatory and permitting pathways for SMRs in the industrial sectors.
- **Communicating needs and options**: Given the range of energy requirements in the mining sector, mining companies should work directly with the nuclear sector on a site-specific basis to communicate the specific technical and operational requirements of an SMR. SMR technology vendors should openly communicate cost and performance data, and those in the design phase should consider design changes to align with the needs of the mining sector.

- **Regional and local considerations**: Future analyses could focus on specific regions and localities, taking into consideration mine-specific requirements, engagement with local communities, regional and local policy frameworks, and infrastructure, including for the transportation of nuclear material such as spent nuclear fuel.

SMRs represent a transformative opportunity for the mining sector, particularly in remote areas. The successful implementation of this technology hinges on collaborative efforts among industry stakeholders, regulatory bodies and the broader community. By addressing the identified challenges and leveraging the potential of SMRs, the mining sector can contribute to global sustainability and clean energy goals.

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SMRs for Mining: Opportunities and Challenges for Small Modular Reactors

This publication on small modular reactors (SMRs) for mining is the first of a series of NEA case studies that assess the opportunities and challenges for SMRs to support decarbonisation of hard-to-abate industrial sectors. The mining sector is particularly challenging to decarbonise. However, mining is essential for the clean energy transition, which depends on various critical minerals such as rare earth elements, niobium, lithium, cobalt and copper for energy infrastructure and technologies for generation, storage and transmission. These materials are commonly located in remote areas, underscoring the imperative to decarbonise off-grid mining.

This NEA case study on SMRs for mining was informed by direct engagement with stakeholders in the mining sector, who identified a range of considerations and barriers to SMR adoption at mine sites related to costs, regulatory aspects, public perception, and operational considerations. A near-term opportunity is quantified for small off-grid mines to replace existing diesel or heavy fuel oil generation with micro-SMRs, with immediate implications for critical mineral mining.

This publication highlights the potential for SMRs to enable sustainable and cost-effective mining essential for the global clean energy transition.

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