FutureBridge

Can Nuclear Power Reduce Energy Costs in Mining Industry by Replacing Fossil Fuels?

ENERGY INDUSTRY

Contents

Nuclear reactors, especially microreactors, are ideal for power generation at mining sites and have the potential to reduce the energy cost significantly, from LCOE of $200-$300 MWh to $90-$330 MWh, as compared to power generated from Diesel generators

- **Energy costs** account for about **25%** of **mining capital expenditure (CAPEX)**. They are **rarely below 10%** and often surpass **25%** of **operating expenditure (OPEX).** This highlights energy's substantial role in mining operations, influencing initial investments and ongoing operational costs
- Therefore, effective energy management and efficiency improvements can lead to considerable cost savings and increased profitability for mining companies

Current Scenario of Power Generation in Mining

Need for an **uninterrupted baseload power** supply: **Diesel is a dominant source**

- **Mines** primarily use **grid connections or internal combustion engines (IC engines)** running on easily transportable liquid fuels like **diesel, heavy fuel oil (HFO), and condensates**. Diesel is the dominant power source at remote sites due to unreliable or unavailable grid power, especially in developing countries
- However, **diesel is expensive and its cost is likely to increase. Frequent electricity outages** can result in **daily losses of millions of dollars**, with additional **time delays** and **safety risks** associated with restarting operations
- The **logistics** of diesel supply in remote locations can also be **challenging**, leading to outages and undermining the economic viability of diesel power. Also, they **convert only 85% of the energy** in fuel to electricity

The Race Towards **Net Zero**: **Replacing Diesel** can **reduce emissions by 50%**

- The mining trucks and mobile equipment are also being increasingly electrified, and hence power requirement of mines will grow much more
- Major mining players are considering renewable energy and storage systems for on-site power, but face investment risks, intermittency issues, and less modularity, potentially exceeding the typical 20-year mining project lifespan

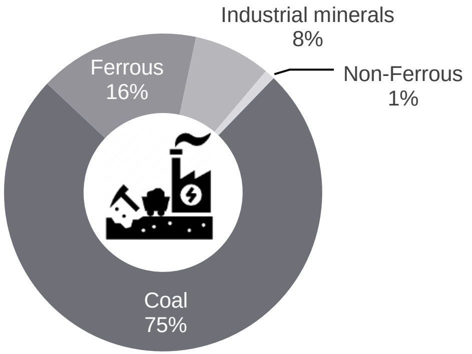
Nuclear Energy as a Viable Recommendation

- A reactor that can be moved to the site at the start of the project and removed during remediation will be a viable alternative
- Small Modular Reactors (SMRs) offer modularity and flexibility, but they also require 10-15 years to become operational
- Microreactors, if commercialized, can be the best alternative for baseload power generation, providing uninterrupted supply and modularity for reliability and redundancy. Their modular nature allows mines to grow in phases without extra investments, benefiting overall economics
- The levelized cost of electricity **(LCOE) from microreactors could be around $90-$330 per MWh**, compared to **$200-$300 per MWh for diesel generators** in remote locations. This implies a **potential** reduction in energy costs by more than half
- However, research and development in terms of Microreactors is still limited, and there should be increased trials and errors before applying them at mining sites. Also, building the Microreactors in a span of less than 36 months (ideal for bigger mining operations) is still a challenge but not impossible

The mining industry is experiencing steady growth with a shift towards increased production of minerals for clean technology while aiming to reduce CO_2 emissions and increase clean energy use by 2030

Mining industry at present

~18 bn tonnes of mined metal & mineral production (2021)



~12 EJ energy consumption / year

~2 to 5 bn tonnes of CO_2e of GHG emissions annually

4% to 7% of global GHG emissions*

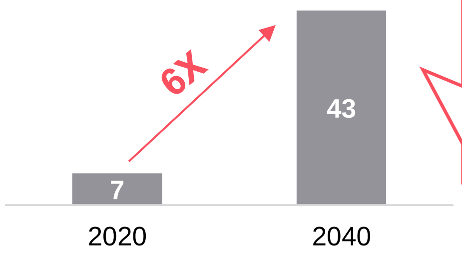
Up to 5% CAGR#

+

Changing scenario

Future mix of commodities will be different

Minerals for clean tech (mil MT)



- Copper, Lithium, and other minerals for RE, EV etc.
- Marginal dip in share of coal in recent years → could continue to the future

Some Important Stats

- The global mining market size was valued at approximately **USD 2.2 trillion** in 2024 and is expected to reach **USD 2.7 trillion by 2025**, growing at a CAGR of **6.5%**
- By **2030**, the global mining sector aims to reduce **CO_2 emissions** by **30%**, driven by stricter regulations and sustainability goals
- Incorporating **renewable energy** can reduce operating costs by up to **25% in existing mining** operations and **50% for new mines**.

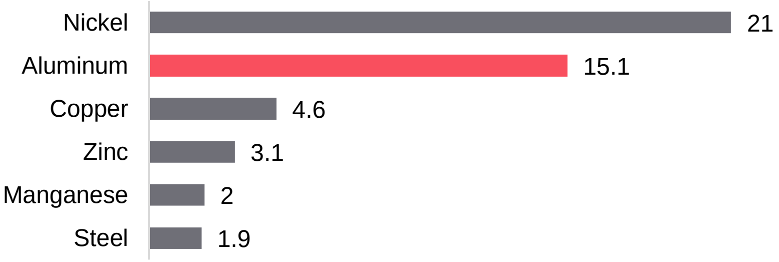
Source: *McKinsey & Co, #Business as usual, Office of The Director of National Intelligence, ^The Weir Group, , IEA, Wood Mackenzei, Brimco, Atlas

The mining sector generates substantial CO_2 emissions, mainly from coal mining and power use. Nuclear Energy can be a viable solution for both reducing GHG emissions and the cost of energy

Overall CO_2 Intensity by Production of Metals

- Every year, the **mining sector** produces **1.9 to 5.1 gigatons of CO_2** equivalent (CO_2e) emissions. The vast bulk of emissions in this industry come from the **1.5 to 4.6 gigatons of fugitive coal-bed methane** that are emitted during coal mining, mostly at underground operations
- **0.4 gigatons of CO_2e** is produced by the **mining industry's power use**
- Roughly **4.2 gigatons** are contributed by the metal industry further down the value chain—what may be regarded as **Scope 3 emissions**—primarily through manufacturing **steel and aluminum**. The combustion of **coal for electricity generation** produces up to **10 gigatons of CO_2**

CO_2 intensity of primary production of metals
(tCO_2/tonne of metal)



Source: McKinsey, Deloitte

Emissions from Diesel Usage: The Low Hanging Fruit

- According to the U.S. Environmental Protection Agency (EPA), **burning one gallon** of **diesel fuel** produces about **22.4 pounds (10.16 kg) of CO_2**

Example:

30-40 liters of Diesel per hour

A Diesel Generator having a **75% load factor and a size of 500 kW**

Operating **24 hours a day** at a remote mining site for baseload power

Emits **107.44 kg CO_2 per hour** i.e **2.58 metric tons per day**

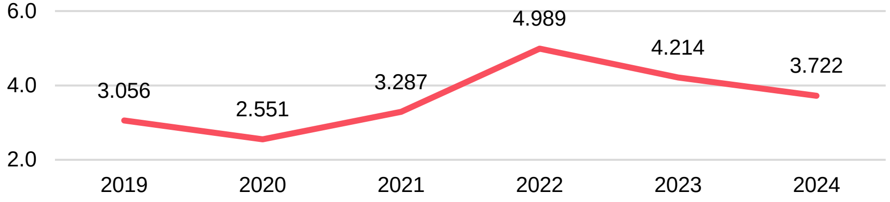
- **Diesel exhaust** releases over **forty harmful air pollutants**, including formaldehyde, arsenic, benzene, and nitrogen oxide (NOx). **NOx is particularly dangerous** as it **traps heat in the atmosphere 300 times longer than CO_2**

- **Nuclear Power** will be an **ideal option** as it can reduce GHG emissions produced by Diesel consumption significantly
- While there are some emissions associated with the construction, fuel processing, and decommissioning of nuclear reactors, these are minimal compared to the continuous emissions from diesel generators. **Nuclear power** has **zero operational emissions**

Nuclear Energy can be the cheapest source of energy generation for mining operations which also offers clean energy

Volatility of Diesel Prices

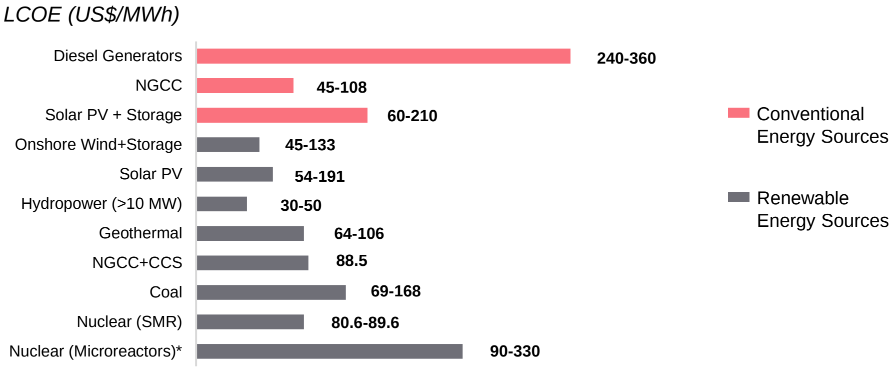
Trend of Diesel Price (USD/gallon), 2019-24



- Since COVID-19, energy markets have seen increased price volatility, with crude oil trading at extreme highs and lows, significantly impacting diesel prices.
- Diesel prices surged 27% at main ports from May to September 2023 due to reduced oil production from OPEC, Russia, and Saudi Arabia.
- The recent Middle Eastern conflict has added uncertainty, keeping oil prices high and exacerbating inflationary pressures. Future diesel price increases are expected as supply constraints and geopolitical tensions persist.

Nuclear Energy as a Viable Alternative

Levelized Cost of Electricity of Baseload power supply (US$/MWh)



****Nuclear Microreactors are cost-competitive with diesel generators for remote applications. The first installation of microreactors has an LCOE of 140 – 410 $/MWh and is estimated to be 90 – 330 $/MWh for future installations.***

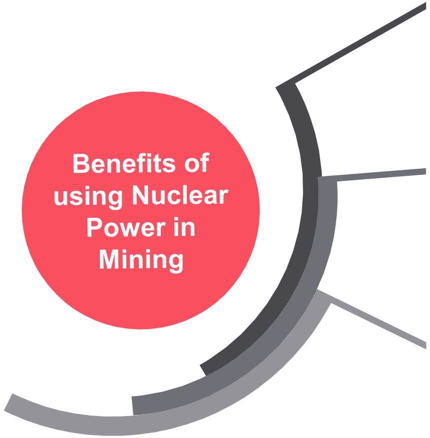
Renewables + Storage or **Nuclear Energy** will be ideal to ensure **uninterrupted power supply at a lower cost.** Renewable Energy + Storage has modularity issues and investment risks hence ***Nuclear Energy is highly recommended***

Despite the **higher upfront costs**, Nuclear Microreactors can offer substantial **long-term savings** and **environmental benefits** due to **lower operating costs and negligible greenhouse gas emissions** while **generating heat**. **Diesel generators**, while **cheaper initially**, incur high ongoing fuel and **maintenance expenses**, leading to **higher overall costs** over time

Source: Breakthrough, EIA, Lazard, IRENA, Ontario Power Generation

Nuclear Energy can be easily integrated into mining operations without the need for new infrastructure or changes to the existing one

Benefits of using nuclear power in Metal Refineries

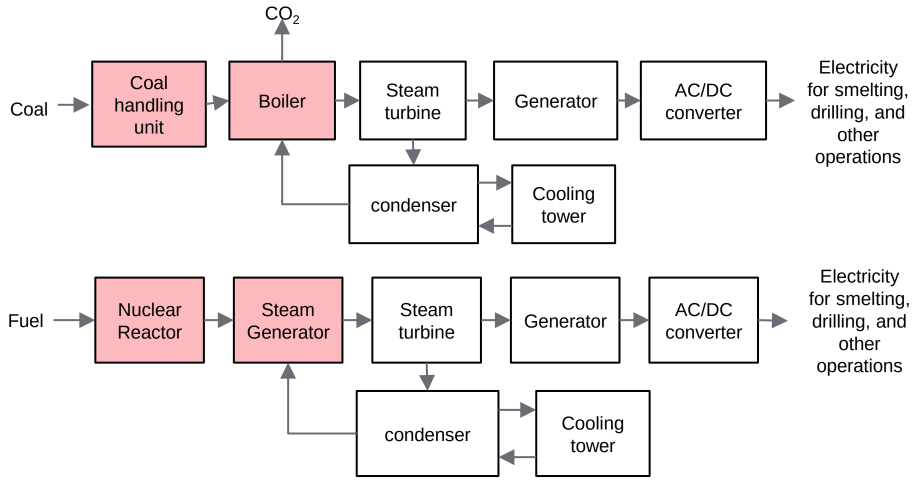


In addition to being a completely dispatchable **baseload** generator, nuclear power can also provide **heat (steam)** for refining

Environmental benefits include **elimination of spills** and **reduction in GHG** emissions

Nuclear power provides **stable and predictable energy prices** over the long term. Most installation costs are fixed, ensuring that electricity prices remain unaffected by volatile crude oil price changes

Advantages of Nuclear Energy Integration



- Nuclear energy can be easily integrated into the mining industry **without building** an entirely new **nuclear plant or making changes to the existing infrastructure**
- **The coal handling unit and the boiler** can be replaced by a **nuclear reactor and a steam generator**. Instead of burning coal, the reactor uses **nuclear fission** to **generate heat** and it heats water to produce **steam** directly, or through a heat exchanger, providing a consistent and high-temperature steam supply. Also, this significantly **reduces the GHG emissions** produced by the coal-handling unit

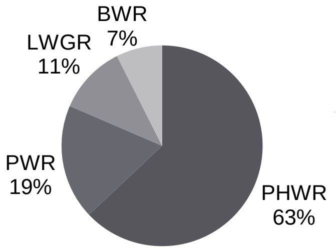
Source: The Mining Magazine, FutureBridge Analysis

Small Modular Reactors are currently gaining some traction due to their modular designs, easy installation, and huge power generation capacity of 300 MW per unit. However, cost is the major constrain for adoption of SMR

Overview

- SMRs are advanced nuclear-fission reactors that have a **power generation capacity** of up to **300MW per unit** – around a **third** of the capacity of traditional reactors and can produce 7200000 kWh per day
- **Prefabricated units of SMRs** could be manufactured and then shipped and installed on-site, potentially making them **more affordable** to build than traditional reactors
- Revival of interest in smaller nuclear power reactors (up to 300 MW) driven by a desire to **reduce capital costs** and to provide power in **off-grid locations**. Power plants equipped with SMRs are designed to **refuel every 3–7 years**, compared to 1–2 years for conventional plants. Some SMRs are even designed to operate for up to **30 years** without refueling

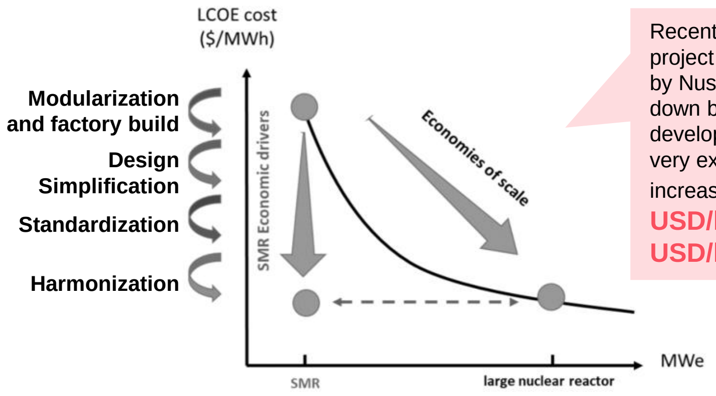
Small nuclear reactor by type (operational)



Total operational small nuclear power capacity: **4,496 MWe**

Source: World Nuclear Association

Financial Aspects- Drivers Compensating Diseconomies of Scale



Recently, an SMR project in Idaho (USA) by Nuscale was shut down because the development phase was very expensive, the cost increased **from 9964 USD/kW to 21561 USD/kW**

- SMRs have many benefits but have a major economic drawback because they cannot benefit from economies of scale due to their smaller size and larger cost requirements
- However, their financial performance can be improved through series production and higher learning rates thanks to **simplification, standardization, modularization, and harmonization** steps.

SMRs have a potential for usage in mining such as fulfilling the baseload power demand and heat generation. Some challenges include longer construction periods of 13-15 years and trial and error risks associated

Benefits of SMR integration in Mining

~62%
Cost advantage in LCOE over Conventional Diesel, offered by SMR

~10 years
Long refueling cycles of SMRs, improving fuel security

0.57 MWh per ton
Exergy can be harnessed by waste heat recovery from smelters producing 260,000 tons of aluminum annually

Major players in SMR technologies for Mining Operations

Westinghouse, NuScale, Terrestrial Energy, GE Hitachi, BWXT (BWX Technologies, Inc.), Rosatom

Source: IEA, ScienceDirect, WoodMackenzie, IAEA, Government of Canada

Recent Examples of SMR Adoption in Mining

- In **Russia**, a floating **RITM-200S** reactor is being considered to supply heat and power to the **Baimskaya copper mine** and mineral processing facility in Cape Nagleynyn, Russia, by 2027 and **ROSATOM** has an agreement to provide power to **Seligdar, a Russian mining company**, using a land-based **RITM-200N** SMR for **gold mining** operations in Yakutia, Russia, by 2028
- In Poland, **KGHM** is exploring the construction of several **NuScale VOYGR** modules for its **copper mining** activities by 2029
- **BWX Technologies** has been contracted by the Wyoming Energy Authority to assess the feasibility of deploying **BANR microreactors** for the power needs of **trona mining operations** in Wyoming, United States
- **GE Hitachi Nuclear Energy** also has an agreement with the **Saskatchewan Industrial and Mining Suppliers Association** to engage with local suppliers on the potential deployment of the BWRX-300 in Saskatchewan, Canada

SMR Adoption for Energy Generation- Unforeseen Challenges

- **SMR development** takes around **10-15 years** to be operational, which is a very long time (e.g. CAREM in Argentina, Russian Ship Borne SMR, etc.). However, some companies like **Westinghouse and X-Energy** have continuously claimed that they can construct SMRs within **36-48 months**
- Since the technology is at a nascent stage, there are **various risks** associated with it. There will be several trials and errors required before going into a fully commercial mode

A recent example of SMR integration in mining includes Rosatom supplying RITM-200S floating SMR for the commissioning of the Baimskaya copper mine which is expected to be operational by 2029

ROSATOM

RITM-200S by Rosatom is an advanced specifically designed for use in floating nuclear power plants. The RITM-200S reactors are an evolution of the RITM-200 reactors used in nuclear-powered icebreakers.

- **Compact Design:** The RITM-200S is designed to be compact, making it suitable for use in floating nuclear power plants and other confined applications.
- **Efficiency:** Improved thermal efficiency and a longer fuel cycle compared to earlier models.
- **Robustness:** Designed to withstand harsh environmental conditions, particularly in Arctic regions.

Key performance parameters for RITM-200S

Parameter	Specification
Reactor Type	Pressurized Water Reactor (Water cooled SMR)
Output Capacity	198 MWe
Fuel enrichment	20% (average)
Refueling cycle	~5-7 years
Design life	40 years
Construction period	8-9 years (estimated)
TRL	8

RITM-200S for Mining Operations

- In **May 2022**, construction began on a floating nuclear power plant equipped with **RITM-200S** reactors to supply power to the **Baimskaya copper mine.** It will be **operational by 2029.**
- The project is being developed by **Atomflot, a subsidiary of Rosatom**, and involves the creation of two floating power units. These units are designed to provide a **total of around 300 MWe** to the **Baimskaya development**, which requires substantial power for its operations.

Rosatom

Rosatom is one of the prominent players in the nuclear energy sector having around 33 power unit installations in 10 countries.

1	2	75
SMR Akademik Lomonosov – operational stage	**Research reactors**	**Years of experience**

Source: World Nuclear News, Atomic Hub

SIMSA and GE Hitachi have joined hands to adopt BWRX-300 SMR for power generation activities in Canada, including mining operations

HITACHI

BWRX-300 by GE Hitachi is an advanced small modular reactor that uses natural circulation and passive cooling isolation condenser systems for a simple and safe operation

- **Modular Construction:** Factory-fabricated modules enable reduced on-site construction time and costs, enhancing deployment efficiency.
- **Cost Reduction:** Estimated to have up to 60% lower capital costs per MW compared to conventional large-scale reactors.
- **Digital Controls:** Incorporates advanced digital control systems for improved operational efficiency and safety.

Key performance parameters for BWRX-300

Parameter	Specification
Reactor Type	Boiling Water Reactor (Water cooled SMR)
Output Capacity	300 MWe
Primary circulation	Natural
Fuel enrichment	3.81% (average)
Refueling cycle	12-24 months
Design life	60 years
Construction period-	24-36 months (claimed)
TRL	8
CAPEX	$3200/ kW net

BWRX-300 for Mining

- In **May 2022**, GEH SMR Canada and the Saskatchewan Industrial and Mining Supplier's Association (SIMSA) agreed to cooperate to support the potential deployment of the BWRX-300 in Saskatchewan.
- SIMSA, a non-profit organization with over 300 member companies from various sectors including manufacturing, construction, engineering, mining, and energy, seeks to connect local businesses with opportunities in the emerging nuclear industry.

GE Hitachi

GE Hitachi is an experienced manufacturer of Boiling Water Reactor (BWR). It has more than 60 years of experience in licensing, fuel, design and manufacturing, and building supply chains.

- **67** — No. of Installations
- **6660** — No. of Patents Issued
- **165,000+** — No. of bundles of BWR fuel designed and produced

Source: GE HITACHI , Nuclear Engineering International

Lower operational and maintenance along with reduced on-site construction time make microreactors a better option than SMR for the mining industry…(1/2)

Overview

- Microreactors are compact, advanced nuclear reactors designed to provide reliable, carbon-free power. They typically generate between **1 to 20 megawatts** of thermal energy (MWth), which can be converted to electrical power to meet the needs of remote areas, military bases, and small communities
- These reactors are highly efficient and can operate for up to **10 years** without refueling
- Microreactors utilize various types of **coolants**, including high-temperature gas-cooled reactors (HTGRs) and designs that employ heat pipes for heat transfer. Multiple designs are progressing through licensing procedures in both Canada and the United States, aiming for deployment soon
- Early microreactors, like the **1-megawatt** reactor that powered a radar station near **Sundance, Wyoming**, demonstrated the **feasibility** of small-scale nuclear power.

Major players in Microreactors

Westinghouse

OKLO

ROLLS ROYCE

ULTRA SAFE NUCLEAR

NANO Nuclear Energy Inc.

Source: Idaho National Laboratory, POWER Engineering

Microreactors Designed for Integration in Mining

- **Oklo's Aurora microreactor**, a **1.5 MW** electric fast reactor, is ideal for remote mining sites due to its small size and long operational life without refueling, eliminating the need for diesel generators and reducing carbon footprints.
- The **eVinci microreactor**, generating **5 MW** of electric power, is ideal for off-grid mining. Its modular, transportable design ensures quick deployment and stable power supply with minimal disruption to operations.
- **The Ultra Safe Nuclear Corporation (USNC) Micro Modular Reactor (MMR)** produces **15 MW** of thermal energy and is considered for remote mining operations, offering scalable, sustainable energy and reducing fossil fuel reliance.

Benefits of using Microreactors over SMRs in Mining

- Today's microreactors are designed to be **small, factory-built, and transportable**. They offer **a flexible and safe** option to provide both electricity and heat, potentially replacing diesel generators. Microreactors can provide **consistent power** for **ore processing**, enhancing the **efficiency and reliability** of mining operations. SMRs on the other hand still require major infrastructural investments due to their large size and pose difficulty in decommissioning after the mining project life is over.
- Most **SMRs take 10-15 years to be fully operational** which is **not ideal** for mining operations. **Microreactors**, on the other hand, can be fully **assembled and transported** to the mining site **reducing the on-site construction time** significantly.
- **Microreactors** are designed to operate for extended periods **without refueling**, which can **lower operational and maintenance costs** compared to SMRs. For **remote mining sites**, microreactors are more cost-efficient as they align with the **specific energy needs**, avoiding the **higher costs of using an oversized SMR**.

Lower operational and maintenance along with reduced on-site construction time make microreactors a better option than SMR for the mining industry…(2/2)

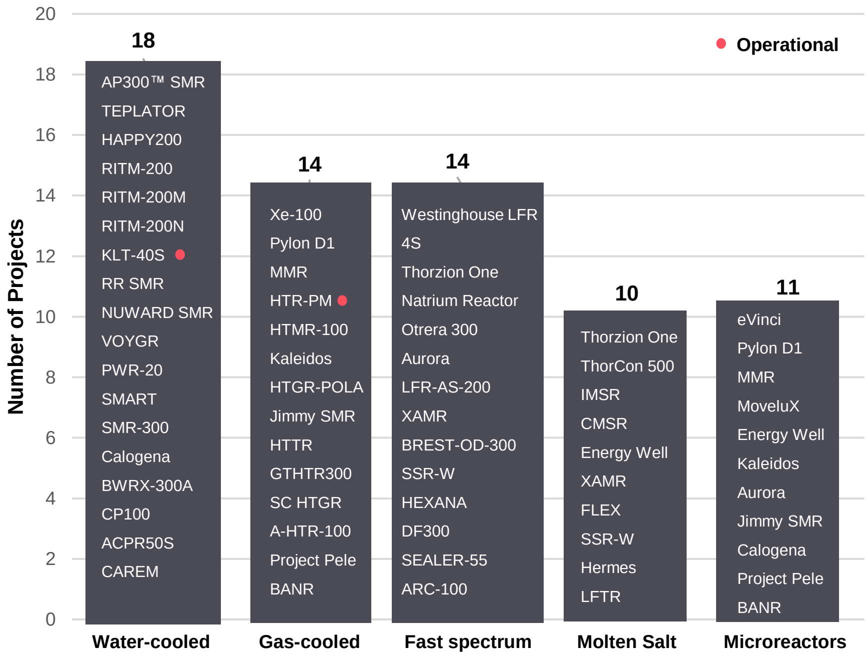
Techno-economic Comparison

Type of SMR	Output Capacity (MWe)	TRL	Construction Cost (USD/MW)	Lifetime (years)	Efficiency
Land-based water-cooled SMRs	30-443	4-6	2,250,000-23,187,500	40-60	~30%
High temperature Gas-cooled SMRs	30-300	6-8	1,550,000-4,373,300	40-60	~50%
Molten Salt SMRs	100-1200	4-6	1,950,000-4,054,266	40-60	~45%
Microreactors/vSMR	**<20**	**6-8**	**5,000,000-35,000,000**	**5-20**	**~40%**

- Microreactors generally have more construction costs per MW than SMRs.
- The total deployment cost of microreactors is lower due to their smaller size and ease of transportation and installation.
- SMRs are better suited for larger-scale power generation, whereas **microreactors** are ideal for smaller, **remote, or off-grid applications like mining** where rapid **deployment and flexibility** are crucial.

- A **typical large mine** might consume around **10 to 50 MW of electrical power** continuously. Assuming continuous operation, a mine consuming **30 MW** of power would use **720 MWh/day**. Assuming a **10 MW thermal microreactor** producing approximately **3.3 MW of electrical power**, **9 Microreactors** would be required
- Microreactors can be **deployed incrementally**, allowing mines to scale their power generation according to their needs and offering lower operational costs due to longer refueling periods

Category-Wise Name Technologies/Projects in SMR

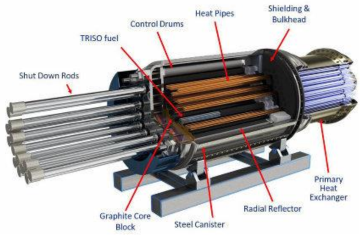


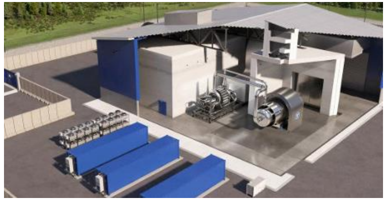
Source: IAEA, ScienceDirect , IDAHO National Laboratory

The eVinci microreactor by Westinghouse is a compact, transportable nuclear power solution for remote mining, offering 5 MWe output with an 8-year refueling cycle and a 40-year design life

Westinghouse

The eVinci microreactor, developed by Westinghouse Electric Company, represents an innovative leap in nuclear power technology, designed to provide reliable and sustainable energy solutions, particularly for remote locations and specific industrial applications such as mining.





FEATURES

- **It eliminates the risk** of commodities arising from **diesel fuel** and the disruptions caused by **seasonal transportation issues** to **isolated locations**
- It can also be seamlessly **integrated** with wind, solar, and hydropower.
- It has an **easy transportability** by rail, barge, or truck in shipping containers

Key performance parameters for eVinci

Parameter	Specification
Output Capacity	5 MWe
Fuel	TRISO (19.75% enriched fuel)
Refueling cycle	8 years
Design life	40 years
Deployment time	30 days
TRL	8
CAPEX	$10000/ kW

eVinci for Mining

- eVinci can produce 5MWe with a 15MWth core design. It provides flexible energy that may be scaled up or down in response to the expansion or decommissioning of mining operations
- The eVinci generates ‘free’ low-grade heat at 1500C which can be utilized for district heating of community infrastructure or pre-heating mine ventilation.
- Mobile equipment can also be electrified using these microreactors

Westinghouse

It is a leading global provider of innovative nuclear technology. With over 130 years of experience in the nuclear industry, it has been at the forefront of nuclear power development, licensing, fuel fabrication, design, and manufacturing.

50% — **Technology share in world’s operating nuclear plants**

12000+ — **No. of Patents Issued**

140+ — **Nuclear plants use the technology and services of Westinghouse**

Source: Westinghouse

The current and future regulatory landscapes for deploying nuclear power in mining highlight the USA's and Canada's established frameworks and the EU's potential for adopting nuclear microreactors

Current Scenario

- The **USA** leads in nuclear power, generating 30% of the world's total and providing nearly 20% of its electricity with minimal carbon emissions. The country has 94 operable reactors with a combined capacity of 96,952 MWe.
- The Nuclear Regulatory Commission (NRC), an independent U.S. government agency, ensures nuclear safety through licensing, inspection, and enforcement.
- Nuclear Energy Innovation and Modernization Act (NEIMA) aims to update NRC regulations, promoting advanced nuclear technologies, which could support mining industries by providing reliable baseload power.

- As of May 2024, **Canada** has 19 nuclear reactors in operation, with a combined capacity of 13.6 gigawatts (GWe). These reactors are located in three provinces, most in Ontario and one in New Brunswick. In 2022, nuclear power generated 13.6% of Canada's electricity.
- Canadian Nuclear Safety Commission (CNSC), an independent regulator that oversees the use of nuclear energy and materials in Canada. The CNSC enforces regulations and by-laws under the Nuclear Safety and Control Act (NSCA).
- AECL develops peaceful nuclear technologies for a variety of applications, including electricity generation, medical isotopes, and nuclear non-proliferation. It also collaborates with various companies to foster innovation and provides economic support.

The **EU** has stringent regulations for nuclear energy, focusing on safety and waste management. Following the Fukushima disaster in 2011, public trust in nuclear power was shaken, leading to tighter regulations and, in some cases, phase-out policies. However, recent energy security concerns have led countries like France and Poland to reinvest in nuclear power as part of their energy strategies

What's Expected Ahead?

- The future of nuclear energy in the USA holds promise with advancements in Small Modular Reactors (SMRs) and increased interest in clean energy sources, despite regulatory and public perception challenges. Efforts in innovation and policy support could enhance its role in achieving carbon neutrality
- In 2020, the USA mining sector emitted around 65 million metric tons of CO_2 equivalent. Flexible regulations will encourage the adoption of nuclear energy in mining, reducing greenhouse gas emissions.

- Canada is collaborating with provinces, territories, and stakeholders to develop SMRs for on-grid power generation, combined heat and power for heavy industry, and off-grid power and district heating in remote communities, aiming for cleaner and more reliable energy solutions.
- The Canadian Minerals and Metals Plan (CMMP) recognizes the potential of Small Modular Reactors (SMRs) to enhance environmental performance and energy security in mining operations and underserved communities
- Canada's SMR Action Plan: A national plan involving over 100 partners, outlining actions to advance SMR development, deployment, and applications in mining

With the EU's emphasis on reducing carbon emissions, mining operations in Europe may increasingly adopt nuclear microreactors to replace diesel generators and other fossil fuel-based energy sources. This shift will help in achieving stringent environmental targets while ensuring a reliable energy supply for remote mining sites

Source: International Atomic Energy Agency (IAEA)

Microreactors can replace diesel generators in mining by offering lower energy costs, scalability, and flexibility while creating new revenue streams through carbon-free imports and providing reliable, low-carbon power for remote sites

Microreactors as a replacement for Diesel Generators

- Mines often rely on diesel generators, which cost around **$0.34 kilowatt-hour**, significantly higher than the electricity costs in some countries. This makes energy one of the major expenses for mining operations. Nuclear **Microreactors** can address this issue by offering energy costs up to **$0.14-$0.41 per kilowatt-hour**
- Mining projects usually have **20-30 years of life**, after which the whole project is decommissioned. Hence **modular nature** of microreactors and **site flexibility** might prove beneficial as they can be **scaled up or down at ease** depending on the requirement. Using **multiple microreactors** will not be an issue for remote mining sites since they have **existing large infrastructure** for transportation.
- Countries **incentivizing carbon-free imports** could create new **revenue streams** for companies using microreactors, increasing competitiveness in global markets

FutureBridge's Lens

- Microreactors typically generate between 1 and 20 megawatts-electric (MWe),making them suitable for isolated and distributed energy applications, including mining operations
- Commonwealth Fusion Systems (CFS) aims to make SPARC project the first fusion reactor to show "net energy gain" by 2025
- For a mining project that requires 50 million liters of diesel per year, a 20-year supply of energy can be secured by a micro nuclear power plant and 2.4 cubic meters of nuclear fuel

Scope of Nuclear Energy in Mining beyond 2024

- The sporadic availability of **electricity output** from renewable sources like solar and wind drives the need for **dispatchable (available on demand) electric generation** capacity. Only **nuclear power plants and fossil fuels can produce dispatchable power**, and only **nuclear power plants emit no emissions**
- **Small modular reactors (SMRs) and Microreactors** are expected to become more widely adopted in remote mining sites, providing a reliable, low-carbon energy source that can replace diesel generators
- Successful **deployment of Microreactors** will require **prototype testing, regulatory approval, and community engagement**. **Canadian Nuclear Laboratories** aims to demonstrate a prototype by **2026**, with **mining companies poised to be early adopters** due to significant potential cost savings
- Miners can count the **energy cost as an operating expense** rather than a capital investment because some **developers of SMR** technology intend to become **independent power producers for remote mines**. For a new project, the **CAPEX savings** from eliminating the construction of a power plant and the pre-purchase and storage of fuel can be substantial
- **Long development timelines** and **slow progress in research** might pose **hurdles** in the path of integration of nuclear power in mining

Recent Initiatives to Implement Nuclear Power in Mining

- Nuclear and mining industries are working together to deploy small reactors (10-50 MWe) at remote sites using diesel, while also developing SMRs for on-grid power in Ontario and New Brunswick
- U.S. DOE's Microreactor Program focuses on creating low-power, transportable reactors to reduce carbon emissions and provide stable energy for remote mining operations

Source: International Atomic Energy Agency (IAEA)

06

Annexure

Other Nuclear Reactors and Their Applicability Assessment in Mining

Conventional large nuclear reactors are unsuitable for mining operations due to high infrastructure and operational costs, safety and security concerns, lack of operational flexibility, and the logistical challenges of constructing and maintaining them in remote locations

Types of Conventional Nuclear Reactors

Type of Reactor	Output Capacity (GWe)	Fuel
Pressurized Water Reactor (PWR)	296.5	Enriched UO2
Boiling Water Reactor (BWR)	60.9	Enriched UO2
Pressurized Heavy Water Reactor	25	Natural UO2
Advanced Gas Cooler Reactor	6.5	Enriched UO2
Light Water Graphite-Moderated Reactor	4.7	Natural U (metal), Enriched UO2
Fast Neutron Reactor (FNR)	1.4	PuO2 UO2

As of 2024, non-operational conventional nuclear reactors include Magnox reactors, RBMK reactors, AGRs, early-generation BWRs and PWRs, early CANDU models, and experimental fast neutron reactors. These have been phased out due to aging infrastructure, economic factors, and safety concerns. Newer, more efficient reactor designs have replaced them.

Applicability in Mining Industry

Due to the large size, higher operational costs, and safety concerns, **conventional nuclear reactors** are **not recommended** for **mining** operations. The reasons are explained below:

Infrastructure Requirements: It requires extensive cooling systems, robust containment structures, and significant land area. Mining sites, especially remote ones, often lack the necessary infrastructure to support such installations.

Cost and Economic Feasibility: Mining operations typically seek more flexible and cost-effective energy solutions. The economic investment required for a large nuclear reactor might not be justifiable given the fluctuating nature of mining operations.

Safety and Security Concerns: Mining sites, often located in remote and sometimes unstable regions, may not be able to provide the level of security and emergency response required for the safe operation of a large nuclear reactor.

Operational Flexibility: Large nuclear reactors lack the operational flexibility required for the varying scale and duration of mining activities, making them unsuitable for such applications.

Remote Location Challenges: The logistical challenges and high costs of constructing and maintaining large nuclear reactors in remote mining areas are prohibitive.

Although nuclear fusion reactors are not yet used in mining, they might hold the potential for providing power, process heat, and energy for deep-sea mining, with advancements such as the ST40 reactor demonstrating significant milestones in plasma confinement and temperature achievements

Possibility of using Fusion Reactors in Mining

Nuclear Fusion reactors **don't find application in the mining industry** yet, but they hold much potential. Some of their benefits include:

- **Power Supply for Remote Mining Operations:** Fusion reactors have the potential to offer mining enterprises in isolated or off-grid areas a reliable and plentiful power supply. This would provide a more affordable, ecological energy option by eliminating the requirement for noisy, expensive diesel generators.
- **Process Heat for Ore Processing:** Fusion reactors may produce high temperatures, which can be utilized to produce process heat for ore processing operations like metal smelting and refinement. This might lessen dependency on fossil fuels and increase efficiency.
- **Energy for Deep-Sea Mining:** Where conventional power sources are impracticable, deep-sea mining operations could be powered by fusion reactors. Fusion's enormous energy production might power the massive equipment and systems needed for underwater mining.

Notable Developments

- **Lawrence Livermore National Laboratory (USA),** in 2022 has demonstrated that nuclear fusion reactors can be perfected into a form that can run a power plant with **abundant fuel, zero meltdown, and nuclear waste**.
- **ITER** is an energy project, run by around 35 countries in southern France, which includes the development of a **magnetic fusion device** called **Tokamak**, which has **500 MW of output capacity.**

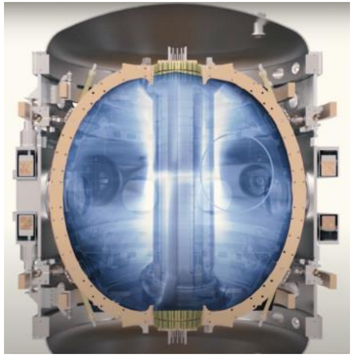
Source: Mining.com, ITER

Compact Fusion Reactor- Potential for usage in Mining Operations

ST40 Nuclear Fusion Reactor

The ST40, developed by **Tokamak Energy Ltd, Princeton, Oak Ridge National Laboratory, and the Institute for Energy and Climate Research**, uses **high-temperature superconductor** technology to enhance plasma confinement and enable a compact reactor design.

Major Radius (m)	Minor Radius (m)	Plasma Current (MA)	Torroidal Magnetic Field (T)
0.4	0.2	2	3



Advantages and Features

- The ST40 has successfully produced ion temperatures exceeding **100 million degrees Kelvin (8.6 keV)**, which is a significant milestone as these temperatures are relevant for commercial magnetic confinement fusion.
- The ST40 employs a **merging-compression plasma formation method**, which is effective for achieving high plasma current and temperature. Also, it has been projected to produce up to **0.5 MW of fusion power.**

FutureBridge's Perspective

This technology has the potential to provide sustained baseload for mining activities with low emissions and less radioactive waste generation but it involves **precise monitoring (operational complexity)** and **high installation costs.**

Thank you

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