# PRODUCTION OF ELECTRICITY USING SMALL MODULAR REACTORS (SMRs) FOR OFF-GRID MNING AND OTHER APPLICATIONS

F. Caron and *J. Abols
*MIRARCO Mining Innovations, Laurentian University*
*Ramsey Lake Road, Sudbury, ON Canada P3E 2C6*
*(*Corresponding author: jabols@mirarco.org)*

## ABSTRACT

Industries need new sustainable sources of energy with a low carbon footprint, especially in off-grid remote areas. The traditional diesel generators used for electricity production in off-grid mining operations and remote communities could be replaced with other forms of energy in the foreseeable future. Small modular reactors (SMRs) are an attractive and emerging source of energy that could replace diesel generators, with the advantages of zero carbon emissions, a long life cycle, and a small land footprint.

There are currently no SMRs licensed or built in Canada. Several SMR vendors however, are at various stages of regulatory approvals. Natural Resources Canada and the Ontario Ministry of Energy have published authoritative works outlining the potential uses for SMRs. In addition, the Canadian Nuclear Laboratories have initiated invitations to build a prototype. These initiatives, together, indicate a bright future for SMRs for various applications, including on-grid, off-grid, mining, remote communities and potential industrial uses. This presentation summarizes the situation in Canada and provides other general aspects of SMRs for mining.

## KEYWORDS

Diesel generation, Electricity, Mining, Off-grid, Small modular reactor, Remote communities, SMR, Zero carbon.

## INTRODUCTION

Small modular reactors (SMRs) are nuclear reactors whose electricity production ratings are below 300 MW (WNA, 2019a). For comparison, conventional reactors, such as those at the Bruce and Darlington stations in Ontario, have power ratings in the 800 MW per unit range. Small mobile reactors are not new: they have been around since the 1950's in submarines and other types of marine vessels. In fact, over 140 ships powered by reactors have accumulated 12000+ reactor-years (r-y) of experience. In the US alone, 6200 r-y were accumulated, covering over 240 million kilometers (WNA, 2019a). In the 1960's, a true land-base modular reactor designed for military purposes was prefabricated and transported to Camp Century in Greenland. It operated successfully from 1961-64 until it was returned to the United States (Vitali et al., 2018). A few years later, a barge mounted nuclear power plant, named Sturgis was deployed, housing a 10 MW nuclear reactor. This plant operated in the Panama Canal zone from 1968-77 and produced electricity and freshwater. More recently, the Russians commissioned a 35 MW working prototype of an SMR, mounted on a floating platform and was moved to the far North. It started operation in late 2019, producing electricity for the city of Pevek (WNA, 2019b).

There was a renewed interest in nuclear energy back in the early 2000's. This "nuclear renaissance" was driven in part by the high price of fossil fuels and the prospects of meeting greenhouse gas emission targets. Reactors in operation at the time were mostly second generation (GEN II) types, built in the late 1960's to the mid 90's. These reactors were ageing and needed replacement, potentially with third generation type reactors (GEN III and III+). Some of these were built, but others were only conceptualized. These reactors were still large (>600 MWe) but offered improvements in safety. Projects involving GEN III and III+ reactors faced hurdles, such as long construction times, complex licensing processes and high costs. As a result, many utilities decided to refurbish existing reactors, extending the life of existing Gen II plants to the mid 2030's and beyond.

With the advancement of technology, safety requirements and new fuel materials, the fourth generation type reactors (GEN IV) are taking a new approach. These new reactors are lower in capacity but with a higher core energy yield and fit in a smaller building footprint. Some GEN IV reactors even claim to consume existing fuel, which would close the nuclear fuel cycle and produce smaller amounts of shorter-lived wastes. These reactors, often referred to as SMRs, can be built in series at a central location and be transported to the point of use, as opposed to custom-built at individual sites.

It is generally recognized that nuclear reactors offer the advantage of producing zero $CO_2$ emissions during operation. With the addition of portability, modularity and a small footprint, SMRs provide a major opportunity for electricity production and could replace fossil fuel generators.

## THE SMR OUTLOOK FOR CANADA

Canada generated 652 terawatt hours of electricity in 2017 (NRCan, 2019). Hydroelectricity was the highest contributor at 60%, followed by nuclear at 15%, coal at 9%, gas/oil/others at 10%, and non-hydro renewables at 7%. Most of the electricity generated in Ontario was from nuclear reactors for 59% of the province's energy supply.

The most authoritative works related to the nuclear industry in Canada, and SMRs particularly, are the SMR Roadmap (2018), and the feasibility study of the Ontario Ministry of Energy by Hatch Ltd (Hatch 2016), referred to as the Hatch report. The SMR roadmap encompasses five working groups: Engagement, Technology, Regulatory Readiness, Waste and Economics & Finance. The SMR Roadmap considers four major markets for SMRs in Canada: oil sands, remote communities & mining, high-temperature steam for heavy industry, and on-grid replacement for conventional coal-fired power plants. The report compared economic calculations of case studies for three sizes of off-grid SMRs (3, 10 or 20 MWe): the 3 & 10 MWe SMRs assumed small off-grid communities, whereas a 20 MWe SMR was an example for a remote mining application.

The output of the comparison was the levelized cost of energy (LCOE). The LCOE is a measure of the sum of all costs used to produce electricity, divided by the total electricity produced over the life time of a source. This metric is generally used to compare types of electricity generation sources. The study concluded that the LCOE of a very small SMR (3 MWe) was similar to that of diesel generation, whereas the other two sizes of SMRs were competitive against diesel. Added benefits of SMRs included reliable operation and no $CO_2$ emissions. Further economies could be achieved if waste heat from SMRs were used for district heating in communities.

The Hatch report focused on the hypothetical deployment at a remote, off-grid mine in Northern Ontario. The study was a composite of six analyses: technical, financial, socio-economic, stakeholders, institutional and environmental. Their analysis was completed based on a short list of 9 vendors comparing their technological compatibility for remote mine deployment, the vendor and technological readiness levels, and the LCOE. One of the key conclusions indicated that all SMR designs under consideration could be economical compared to diesel. They also concluded that SMRs can provide reliable electricity production for a mining operation, with a low carbon footprint. The technical readiness level of the reactors that they have examined, however, is generally at the medium level.

The Canadian Nuclear Laboratories (CNL) have issued a request for expressions of interest (RFEI) for vendors to build an SMR demonstration unit at one of their two licenced sites (Chalk River ON, and Pinawa MB (CNL, 2017). They recognize that for the market to be ready, the industry must work together to bring the SMR technology to a working model. As such, it is our opinion that deployment of reactors in Canada will likely follow one of two processes, or both:

(1) Vendor review by the Canadian Nuclear Safety Commission (CNSC, 2019): this step is a pre-licensing vendor review. It deals mostly with the safety aspects of the reactor designs from vendors. Currently, 12 vendors are at different stages of review. With pre-licensing, a vendor could apply for a license to build a reactor after engagement with a client. A prototype would not be necessary.
(2) The RFEI process for an SMR demonstration project with CNL (CNL, 2017): this process evaluates vendors for the technical and operational readiness of their SMR design, and their readiness to build a demonstration. There are currently four vendors who are at advanced stages of application. Although this process is not mandatory, vendors must go through CNSC licensing prior to building and demonstrating.

## OFF-GRID NEEDS FOR MINING AND COMMUNITIES IN CANADA

Several sources, including the SMR roadmap and the Hatch report, recognize that SMRs are an attractive opportunity for off-grid applications such as mining and remote communities. For instance, Wojtaszek (2017) has reviewed the NRCan database for remote communities. He mentioned that, at the time, 280 communities were not connected to the main North American grid, of which 211 relied on fossil fuel for electricity production. The fossil fuel of local plants corresponds to installed capacity of 337 MWe, with most plants producing between 0.1 and 2 MWe.

The same study mentioned that 32 operating or planned off-grid mines relied on diesel generators. The total demand for these mines is 658 MWe, with individual power requirements ranging from 4 to ~125 MWe. The demand for most of these mines is between 5 to 30 MWe.

Including oil sands extraction, cogeneration and improvements in efficiencies, he concluded that over 600 sites constitute the potential off-grid market for SMRs in Canada. The combined demand for these sites is over 35 GWe. Most sites are small communities with small demands, whereas the resource extraction projects (mining, oil sands) required most of the energy.

## RISKS – TECHNICAL AND NON TECHNICAL

The technology readiness level (TRL) of SMRs scored between 4 and 7 (on a 1-9 scale), depending upon the vendor. The Hatch report indicated that a group of established companies have technical and financial resources, but fragmented interest in small reactors. Small companies at the venture level have a strong interest in small reactors but lack resources. The technologies and markets have undoubtedly advanced since the report was published in 2016; unbiased and agnostic comprehensive reviews are ongoing with the CNSC and the RFEI-CNL processes to alleviate these risks.

Commercial maturity is a risk identified by the Economic and Finance Working Group (EFWG) of the SMR roadmap (EFWG, 2018). The group has suggested that government-industry partnerships should support R&D and demonstration to achieve commercial maturity. Among other recommendations, the group mentioned that reducing costs of financing is an important hurdle to overcome for bringing SMRs to market. Some of the financial risks, for example, are associated with construction (cost overruns, long schedule times, under-developed supply chain).

Externalities arising from electricity production can be significant risks that are not necessarily built into the costs of SMR deployment. These risks (also costs) are incurred with environmental health, air pollution, crop yields, climate change at large; those risks are generally borne by society in general (WNA, 2020). Recently, to compensate for these risks, governments around the world are using tax on $CO_2$ emissions as an incentive to decrease emissions (ibid). Many other non-technical risks include political risks (Country risk, resource nationalism), commodity price risks, exchange rate risks, corporate risk, among others (Trench et al., 2014). Even though Canada is generally considered a safe political place, land access, land claims, social risk (including protest marches) are issues for the resource extraction industry (CBC, 2020).

## ECONOMIC PROSPECTS OF SMRs FOR MINING AND COMMUNITIES

Diesel generators for remote off-grid mines and communities are the incumbent technology and the choice target for benchmarking economic calculations. Both the SMR roadmap and the Hatch report compared the LCOE of SMRs vs diesel generation; these reports have not included low-carbon emerging technologies such as wind generation. In addition, storage technologies in an energy park with a microgrid controller might become options in the future (Moore & Gnagnapragasam, 2018; Baidya et al., 2019).

The costing model used in the Hatch report includes the following input capital expenditures (CAPEX) for the diesel generator: the generator itself, a backup diesel generator, unit addition, and replacement. The operating expenditures (OPEX) for diesel included the fuel itself and the engine rebuild. The CAPEX listed for an SMR are more complex: the plant itself, a diesel generator, energy storage, initial site licensing cost, spent fuel storage, decommissioning, core-redeployment credit, and unit addition. The OPEX is the diesel fuel (for the backup generator), labor cost, security, nuclear insurance, other fixed maintenance, and $CO_2$ credit.

The EFWG of the SMR roadmap used similar CAPEX and OPEX parameters but went into more detail in some areas. For example, they focused on three sizes of SMRs for two different uses (community, mining); they calculated the LCOE for a first unit, which would be the most expensive because it is the first of a kind (FOAK). A builder could achieve economies of multiples by building subsequent units (nth-of-a-kind, NOAK), saving on the learning process and the tools used in building the FOAK, and the construction process would be shorter.

The cost comparison for the two sources is given in Table I. The table suggests that SMRs would achieve significant savings, on a kWh basis. This Table is an oversimplification; a few factors need to be considered with this type of comparison:

*The LCOE of SMRs were advantageous compared to the 10-20 MWe diesel generators; this metric was neutral or similar for the very small SMR of 3 MWe.

*SMRs are capital-intensive, but low maintenance. The LCOE of the SMR, particularly for the SMR roadmap, assumes favorable factors of a NOAK.

*The LCOE of diesel generators are very sensitive to the price of fuel. The carbon tax, if implemented, would also contribute to the diesel LCOE. A 20 MWe fleet of diesel generators can consume up to 37 M Litres of diesel fuel annually, emitting approximately 105 000 metric tons (mt) of $CO_2$ equivalent. 20 MW x 8760 h x 90% x 240 L/MWh gives 37.8 M Litres of diesel. That would be $37.8 M/year. The GHG potential is 2.79 kg $CO_2$/L of diesel (Hatch; FC confirmed this value independently at 2.69). That amounts to ~105 000 mt $CO_2$/year, or $2.1 M /year at $20/mt tax annually, if implemented.

*neither report included the costs of shipping and handling fuel, nor the capital expenditures of holding capacity (e.g., tanks).

*Alternative technologies such as wind are now becoming cost competitive. Some mines own and operate wind turbines or have engaged with an operator (Raglan, Diavik), or are in the process of doing so (Agnico Eagle).

SMRs are capital-intensive and have low maintenance costs, compared to diesel, and would ideally be suited for long-projects (long life of mine, long-term for a community; see Wojtasek, 2017). Other costs relate to the operation: mine operators have learned to utilize diesel generators to manage load shifts. Managing base loads with SMRs would be different and would require training, as not all SMR designs have an easy load following capacity (Hatch, 2016). It has been suggested that an SMR might best be integrated in an energy park with renewables such as wind, a microgrid controller, coupled with storage technologies (Moore and Gnagnapragasam, 2018; Baidya et al., 2019, Stickler et al., 2017). In this context, it might be advantageous for a mine owner to engage with an experienced and reputable nuclear and/or microgrid operator to pay for services that would provide reliable power for operating a mine.

Table I. Comparisons of LCOE for a diesel generator and generic SMRs

| Item | Source: Hatch report (Hatch, 2016) ($CAD /kWh) | SMR roadmap EFWG (EFWG, 2018) ($CAD /kWh) |
|---|---|---|
| LCOE diesel (base case) | $0.345 | $0.320 |
| LCOE SMR | $0.193 - $0.288 (25 MWe SMR) | $0.175 (20 MWe SMR NOAK) - $0.288 (3 MWe NOAK) |
| Potential savings (compared to diesel) | $0.057 - $0.152 | $0.032 - $0.145 |

## CONCLUSIONS

Studies completed to date show that SMRs would be advantageous for a mine operator based on the overall cost, long lifetime for the reactor, long refueling schedule, plus averted $CO_2$ emissions when compared with diesel. With the addition of portability, modularity and a small footprint, SMRs provide a major opportunity for electricity production and could replace fossil fuel generators. SMR designs are advancing rapidly, however commercial maturity is still a risk. Government-industry partnerships are recommended to support R&D efforts and a full-scale demonstration to achieve commercial maturity. SMRs could pose difficulties for a mine operator due to challenges such as licensing, social acceptability and waste handling. A mining focused research facility, such as Mirarco, is well placed to assist in navigating these challenges. An SMR alone produces a good base load, however load following and backup would likely be needed as a part of an energy park that comprises other renewables, at an additional cost. Finally, a mine owner might not want to become an SMR owner or operator; a good model is for a mine operator to engage with a nuclear operator in a joint venture for ownership and/or operation.

## REFERENCES


Arriaga, M., Brooks, M., & Moore, N. (2017). *Energy access – the Canadian context.* (Excerpted from Waterloo Global Science Initiative's OpenAccess Energy Blueprint No. Creative Commons License BY-NC). Waterloo, ON. Retrieved from http://wgsi.org/sites/wgsi-live.pi.local/files/Energy_Access_Canadian_Context_Infographic_Spread_and_Section-OpenAccess_Energy_Blueprint_WGSI_2017.pdf

Baidya, D., Ghoreishi-Madiseh, S. A., & Scoble, M. (2019). Energy portfolio versus sustainability of mining industry. In *The 9th International Conference on Sustainable Development in the Minerals Industry*. Sydney, AU, 2019 May 27-29.

CBC. (2020). Large crowd blocks downtown street in protest against mining industry convention. Retrieved March 14, 2020, from https://www.cbc.ca/news/canada/toronto/protest-front-street-pdac-mining-industry-convention-toronto-1.5481698

CNL. (2017). *Perspectives on Canada's SMR opportunity, Summary Report*. Canadian Nuclear Laboratories. Retrieved from https://www.cnl.ca/site/media/Parent/CNL_SmModularReactor_Report.pdf

CNSC. (2019). Pre-Licensing Vendor Design Review. Retrieved from https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm?pedisable=true

EFWG. (2018). *Economic and Finance Working Group of the SMR Roadmap*. Retrieved from https://smrroadmap.ca/wp-content/uploads/2018/12/Economics-Finance-WG.pdf

Hatch. (2016). *Feasibility of the Potential Deployment of Small Modular Reactors (SMRs) in Ontario*. Ontario Ministry of Energy. Retrieved from http://ontarioenergyreport.ca/pdfs/MOE%20-%20Feasibility%20Study_SMRs%20-%20June%202016.pdf

Moore, M. A., & Gnanapragasam, N. (2018). Energy storage coupled with vSMR for remote communities. In *Pacific Basin Nuclear Conference*. San Francisco, CA Sept 30-Oct. 5, 2018.

NRCan. (2019). Electricity facts. Retrieved from https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/electricity-facts/20068

SMR Roadmap. (2018). *A call to action: a Canadian roadmap for small modular reactors*. Ottawa, ON: Canadian Small Modular Reactor Roadmap Steering Committee. Retrieved from https://smrroadmap.ca/

Sykes, A., Trench, A., & Packey, D. (2014). *Non-Technical Risks and Their Impact on the Mining Industry* (2nd ed.). The AusIMM guide to good practice. Retrieved from DOI: 10.13140/RG.2.1.1413.5445

Vitali, J. A., Lamothe, J. G., Toomey, C. J. J., Peoples, V. O., & Mccabe, K. A. (2018). *Study on the use of mobile nuclear power plants for ground operations* (No. Deputy chief of staff G-4). UKnited State Army. Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/1064604.pdf

WNA. (2019a). Small Nuclear Power Reactors. Retrieved from https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

WNA. (2019b). Russia connects floating plant to grid. Retrieved from https://www.world-nuclear-news.org/Articles/Russia-connects-floating-plant-to-grid

WNA. (2020). Externalities of electricity generation. Retrieved from https://www.world-nuclear.org/information-library/economic-aspects/externalities-of-electricity-generation.aspx

Wojtaszek, D. T. (2017). Potential off-grid markets for SMRs in Canada. *CNL Nuclear Review*. https://doi.org/10.12943/CNR.2017.00007.