FULL ARTICLE

OPPORTUNITIES AND CHALLENGES RELATED TO THE DEPLOYMENT OF SMALL MODULAR REACTORS IN MINES IN THE NORTHERN TERRITORIES OF CANADA

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Small modular reactors (SMRs) are being touted as safer, more cost effective, and more flexible than traditional nuclear power plants. Consequently, it has been argued that SMR technology is pivotal to the revitalization of the nuclear industry at the national and global levels. Drawing mainly on previously published literature, this paper explores the opportunities and challenges related to the deployment of SMRs in the northern territories of Canada.

The paper examines the potential role of SMRs in providing an opportunity for remote mines in northern Canada to reduce their vulnerability and dependence on costly, high-carbon diesel fuel. The paper also outlines and discusses some of the potential socio-economic barriers that could impede the successful introduction of SMRs in the territories. These issues include: economic factors (such as the price of primary minerals and economics of mineral exploration, and the cost of SMR deployment), the lack of infrastructure in the territories to support mining developments, and the issues pertaining to the social acceptance of nuclear power generation.

1. Introduction

Small modular reactors (SMRs) are being touted as safer, more cost effective, and more flexible than traditional, larger-scale nuclear power plants. Proponents also point to the potential economic and social advantages and benefits of introducing SMRs. Consequently, it is asserted that SMR technology is pivotal to the revitalization of the nuclear industry at the national and global levels.

In Canada, proponents [1] have suggested that the deployment of SMRs may provide an opportunity for communities and businesses in northern Canada to reduce their vulnerability and dependence on costly, high-carbon diesel fuel. Other potential benefits include job creation within the nuclear industry's supply chain, income from export of SMR technology, and reduction of air pollution and greenhouse gas emissions emanating from the utilization of diesel-fired generators for industrial mining activities in the north (the Yukon, Northwest Territories, Nunavut, and the northern parts of Ontario, Manitoba, Saskatchewan, Alberta, and British Columbia). Boosting economic activity in the Arctic region could also strengthen Canada's sovereignty over that region.

Despite these potential advantages, the successful deployment of SMRs in Canada could be impeded by several issues. These issues include: economic factors (such as the price of primary minerals and economics of mineral exploration, and the cost of SMR deployment), technical issues related to the construction of SMRs that are suitable for the niche markets in northern Canada (SMRs within the lower power level range), the lack of infrastructure in the territories (Yukon, Northwest Territories, and Nunavut) to support mining developments, and the issues pertaining to the social acceptance of nuclear power generation.

Drawing mainly on previously published literature, this paper explores the opportunities and challenges of deploying SMRs in mining establishments in the Canadian territories. The paper examines the potential role

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of SMRs in providing an opportunity for remote mines in the northern territories of Canada to reduce their vulnerability and dependence on costly, high-carbon diesel fuel. For example, building an SMR industry in Canada could complement the country's extensive expertise in uranium mining, reactor technology, plant operation, nuclear research, and environmental and safety standards, thereby enhancing Canada's ability to offer services throughout the entire nuclear life cycle. The paper also outlines some of the broader technical, economic, and social barriers that could impede the successful introduction of SMRs in mines in northern Canada.

SMRs are defined by theInternational Atomic Energy Agency as reactors producing less than 300 MW_e of electrical power [2]. Given the variety of niche markets for SMRs in Canada, for the purposes of this paper micro-SMRs are defined as reactors generating 25 megawatts electricity (MW_e) or less. Although micro-SMRs are the focus of this paper, the term SMRs will be used throughout the paper because that is the term that is most commonly used in the industry and by the general public. Section 2 discusses the potential mining markets for SMRs in the northern territories of Canada. Section 3 outlines the main barriers to the deployment of SMRs in mines in the territories. Section 4 provides a balanced discussion of the opportunities and challenges related to the potential deployment of SMRs in northern mines Section 5 provides concluding statements on the topic.

2. SMRs and Potential Mining Markets in Northern Canada

The mining industry[1,2] is an important part of Canada's economy, contributing $52.6 billion to the Gross Domestic Product in 2012, while employing 418 000 workers in 1264 industrial and commercial establishments across the country [3].

The northern regions of Canada have an abundance of natural resources, and mining exploration and development is expected to be an important driver of the economy in this part of the country over the course of the next 25 years. According to the Conference Board of Canada [4], the production of metallic and nonmetallic minerals from the northern part of Canada[3] is expected to grow by 91% from 2011 to 2020, with a compound annual growth rate of 7.5%. This growth in output would lead to a doubling of the value of Northern metallic and nonmetallic mineral output, from $4.4 billion in 2011–2012 to $8.5 billion in 2020.

[1] Mining refers to both metal and nonmetal mining activities.

[2] This refers to mineral extraction, smelting, fabrication, and manufacturing activities related to metallic and nonmetallic mining.

[3] This refers to northern Canada as defined by the Northern Development Ministers Forum (NDMF). The NDMF defines the North as the three territories (Yukon, Northwest Territories, and Nunavut) and the northern extent of seven provinces (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Québec, and Newfoundland and Labrador).

2.1. Untapped natural resources in the territories as potential markets for SMRs

The vast expanses of Canada's 3 territories (the Yukon, the Northwest Territories, and Nunavut) are believed to contain much of Canada's untapped natural resources. The region has significant deposits of natural resources including gold, diamonds, copper, lead, zinc, uranium, iron ore, tungsten and base metals [5]. One of the world's largest iron ore deposits in the world is in the northeastern Yukon (the Crest deposits). The Selwyn basin in the Yukon has one of the world's largest undeveloped lead-zinc deposits. Exploration initiated in 2005 reported the indicated[4] resource at 154.4 million tonnes at 5.35% zinc (Zn), 1.86% lead and the inferred[5] resource of 231.5 million tonnes grading 4.54% Zn and 1.42% lead (Pb), making this potentially the largest zinc deposit in the world [5].

The tungsten (W) deposits in the Northwest Territories (but only accessible through the Yukon) are estimated to contain 15% of the world's total reserves [5]. In addition, the Northwest Territories is the largest producer of diamonds in the Americas [6]. Geological data suggest that Nunavut offers the promise of vast mineral wealth including gold, lead, zinc, and diamonds. The Kitikmeot region of Nunavut, which is located within the Canadian Shield, is known to host base metals, diamonds, gold, lithium, platinum group elements, and uranium [7].

Reliable, clean, and cost-effective sources of power generation are required to exploit these natural resources. Given the vast size of Canada's northern territories, there are many differences throughout this area, notably with respect to climate, remoteness, and availability of critical infrastructure for economic development. Regardless of these differences, energy infrastructure costs in the territories tend to be relatively higher compared with areas that lie to their south for a variety of reasons. Some of these reasons include higher transportation costs for fuel and equipment, smaller and more dispersed population, higher operating and maintenance costs, specialized infrastructure required for use in cold climates, and the greater need for space heating [8].

The population distribution within the territories is clustered in several medium-sized cities, small mining towns,

[4] Resource whose quality and quantity have been estimated partly from analyses and measurements and partly from reasonable geologic inferences.

[5] Resource in identified but unexplored deposits whose quality and quantity have been estimated from geologic projections.

ice-road communities, and fly-in communities. Consequently, the electrical systems in the 3 territories are characterized by relatively small clusters of customers separated by large distances. Whereas southern Canada has the population and industrial density necessary to support building high-capacity transmission lines to interconnect customers to large centralized electricity generation sites, for many communities in the north it is more economically practical to avoid interconnecting transmission lines and instead install and operate isolated or "islanded" generators located close to customer loads (for example, each generator is typically located within the community it serves). Consequently, most industrial load centres in the north are electrical islands. Given the geography and settlement patterns in the north, distributed power generation may be a more pragmatic way to promote growth and economic prosperity within Canada's remote yet resource-rich territories. Figure 1 shows the electricity grid for the Northwest Territories and

Source: NWT Power 2012

FIGURE. 1 The electricity grid for the North West Territories.

depicts the distributed nature of electricity generation in Northwest Territories.

2.2. Mines and diesel power generation in the territories

Mines are large consumers of power, and can be a driving force for the expansion of electricity generation capacity. Lack of access to reliable and cost-efficient power is creating a significant barrier to resource development projects in Canada's territories [4]. Mining projects in the territories are often far off the power grid, resulting in mines being mainly powered by electrical generators driven by diesel-fueled internal combustion engines (diesel generators).

Diesel power generation has many advantages. Some of these advantages include high levels of operational reliability, scalability, portability, and relatively lower upfront capital expenditures. Diesel generators also have a higher degree of flexibility to deliver base and peak load electricity because it can rapidly change output. Because diesel power generation is a mature technology, there is a continuing trend of improving efficiency on generators. These improvements include waste heat recovery and implementing automation and controls for matching output and loads [9]. Consequently, the diesel technology is a mature and well-understood technology.

However, despite these basic advantages of diesel generators, there are many shortcomings related to the use of this form of power generation. Research has shown that diesel engine exhaust contains pollutants in a complex mixture of gases and particulates that can be harmful to human health [10]. Health studies show that exposure to diesel exhaust primarily affects the respiratory system and worsens asthma, allergies, bronchitis, and lung functions. There is some evidence that diesel exhaust exposure can increase the risk of heart problems, premature death, and lung cancer [10]. Diesel generators create air pollution and greenhouse gases emissions, environmental contamination due to fuel leaks and accidental spills, and expose industrial establishments to financial risks and instability through fluctuations in diesel fuel prices and high fuel transportation costs.

The major disadvantages of diesel are the high and unpredictable fuel costs and the expensive and difficult logistics especially related to northern deployments. For example, depending on the location, the cost of generating electricity using diesel generators could make up between 10% and 30% of the capital costs of a new mine [11]. The operating cost of diesel power generation is also high. For example, NWT Power, the main electric utility in the Northwest Territories, estimates that, for start-up mines in the territory, the cost of diesel generation includes an average annual operating and maintenance cost of $5.3 million and an annual average fuel cost of $27 million [11]. The construction of seasonal winter roads required for transportation of diesel fuel and other materials also adds to the cost of power generation in mines. For example, the 3 diamond mines in the Northwest Territories spend between $15 and $20 million to construct seasonal roads annually [12]. Thus, seasonal storage and shipping of diesel and other products related to diesel generation plant can negatively affect cash flow and add to the costs of operation. All these annual costs are in addition to the initial capital investment for a diesel generator, which has an estimated average cost of $60 million per generator [11]. These high costs of operation are mirrored in mining sites powered by diesel engine in other parts of the north.

Consequently, providing a reliable source of power with a low environmental impact and at a lower cost than diesel power generation can improve the business case for a mine under development or extend the life of an operating mine. Given these conditions, SMRs have been suggested and promoted [1] as an energy solution for remote off-grid mining locations in the northern territories, especially in areas where the use of natural gas and hydroelectricity are not feasible and the main source of energy for industrial activities is diesel fuel. Currently, none of the mines in operation in the north are connected to the limited transmission grids.

The power requirements for mines vary depending on factors such as the type of mineral being mined, the quantity of ore mined, other electricity needs, and climatic conditions. For example, the Diavik diamond mine's site (Northwest Territories) is powered by 2 diesel power plants, which provide a total 40 MW_e of capacity [12]. According to NWT Power, a typical off-grid diesel powered mine in the Northwest Territories has an electrical load averaging 10 MW_e [11]. NWT Power estimates that proposed mines in the Northwest Territories will require at least an additional capacity of 100 MW_e of new installed capacity [11], whereas Yukon Power (the electric utility in the Yukon) [13] estimates a minimum power requirement for proposed mines of at least 60 MW_e (even after the expansion of its Mayo B hydro generation plant). As shown in Table 1, proposed mines in Nunavut will require additional power capacity ranging from 150 to 200 MW_e. Given that Nunavut's current electricity base load is entirely provided by diesel generation, these proposed mines could be potential markets for SMRs.

Table 1 [11, 14–24] shows the operating and planned mines in all 3 territories and their power requirements.

Given the technical, regulatory, and economic barriers faced by SMRs, these mines outlined in Table 1 may not be candidates for deployment of SMRs. However, the table gives an indication of the variation in the magnitude of the power needs of mines.

TABLE 1. Estimated power capacity of existing and potential mines in the Northwest Territories, Nunavut, and the Yukon.

Mining projects	Capacity (MW)
Northwest Territories	
Diavik	40
Ekati	15
Snap Lake	15
Sea Bridge Courageous Lake* [14]	30
Canadian Zinc* [15]	7.5
Avalon Thor Lake*	10
Gahcho Kue*	10
NICO*	15
Yellowknife Gold*	10
Nunavut	
Meadowbank [16]	26
Meliadine* [17]	25.6
Hackett River* [18]	25
Izok Lake* [19]	5
High Lake* [19]	10.5
Roche Bay* [20]	30–50
Back River* [21]	10–20
Kiggavik* [22]	22
Mary River	Unknown
Yukon	
Mactung Mine Project [23]	10
Casino* [24]	150
Selwyn Resources* [23]	35
Eagle Gold [23]	5
Ketza [24]	5

Note: This list of proposed mines in the Territories is just for illustrative purposes and may not be an exhaustive list.
*Refers to a proposed mining project.

3. Obstacles to the Deployment of SMRs for the Exploitation of Natural Resources in the Territories

Although the deployment of SMRs in mining establishments in the territories could be very beneficial on many fronts, there are many obstacles that need to be overcome before this technology can be successfully deployed in this region. These challenges are outlined and discussed in this section.

3.1. Economics of SMR manufacturing and deployment

Proponents of SMRs point to features of the technology that make SMRs economically attractive [25]. These characteristics include among others, their modularity and their potential for deriving economies of mass production in factories, lower upfront capital costs, reduced construction times and flexibility of matching SMRs to niche markets. Other economic advantages of SMRs include the creation of domestic manufacturing, construction, and operation jobs in countries involved.

SMRs have never been produced on a commercial scale in North America and Western Europe; hence, the actual cost of production of the modules is yet unknown. Given the variety of SMR designs under consideration, costs may vary considerably. A business case study on the commercial viability of SMRs must take the following factors into account.

3.1.1. Level of customer needs/interests

Given the risk-averse tendency of the nuclear industry, the market demand for modules to justify investments is an important factor in the commercial success of SMRs. The demand for SMRs to supply power for extracting natural resources will also be influenced by the price of crude oil, gold, diamonds, etc. The prices of these products in turn are dependent on the global demand and health of the world economy. Another issue that may impact demand for SMRs is the variety of SMR designs that are being proposed. The potential market demand for SMRs is tens to hundreds of units. However, given the variety of SMR designs under commercial development, the question arises about how much demand exists for one particular type of SMR. A consolidation of SMR designs and vendors to increase market shares may be necessary to ensure sufficient demand to ensure economic viability for the prospective SMR vendor(s).

3.1.2. Economies of factory production of SMR modules

Researchers agree that for SMRs to be competitive, mass production is needed [25]. The ability of SMRs to be mass-produced in factories and shipped to operation sites to reduce costs is said to be one of the main advantages of the technology [26]. For this goal to be achieved, SMRs need to be manufactured on a highly efficient production line. Single SMR units could have significant one-time site-related costs. Thus, where possible, the operation of clusters of SMRs may be more economical. The concentrated nature of minerals in the territories could provide an economically viable scenario for having clusters of SMRs in operation, thereby reducing the offsite-related costs. Added to the issues mentioned above is the intense foreign competition, primarily by state-owned or state-aligned nuclear reactor vendors.

3.1.3. Regulatory requirements and cost of SMRs

SMRs using innovative technologies may require regulatory oversight that may increase the cost of production and operation of SMR modules.

3.1.4. Cost of waste management and decommissioning

Given the variety of SMRs designs under consideration, fuel waste management and decommissioning costs are uncertain. Different SMRs may produce different waste streams, with different characteristics. Consequently, any business case study on the commercial viability of SMRs must take waste management costs into account. It is also pertinent to note that any SMR technology adopted will also have to take into account the long-term implications for handling and storage of nuclear waste in Canada.

3.1.5. Government policies on SMRs

Government (federal and/or territorial) policies to promote the use of SMRs could include incentives for first adopters, use of first-build SMRs at government facilities such as military bases, power purchase agreements, production tax credits, loan guarantees, clean energy policies such as a carbon tax policy, and export policies.

Further research on the potential economic competitiveness of SMRs in the territories would help to better understand all the viable energy options. Although a strong business case for SMRs in mines in the territories is important for commercialization of SMR use in these mines, the use of SMRs in remote mines in the territories could also provide a more reliable source of power supply to mines. This reliability could alleviate the added cost and risks associated with the shipping and storage of diesel fuel during the short-window shipping period in the north.

3.2. Infrastructure gap in the north

The lack of critical infrastructure, such as all-season roads, ocean and waterway ports, and railways required for the transport of equipment and extracted mineral resources is a deterrent to the exploitation of the natural resources in the territories because it raises the cost of doing business. This infrastructure gap makes it less economically attractive to invest in these mining ventures. Being so remote from markets, only the high-value natural resources justify the huge investments in new infrastructure. However, once infrastructure is established for a given mining project with a high-value resource, it may be possible to utilize the same infrastructure to economically exploit nearby natural resources of lower value.

A survey of Mining Companies by the Frasier Institute [27] found that of all Canadian jurisdictions, Nunavut, Northwest Territories, and Yukon have the greatest percentage of companies reporting being deterred from investing due to infrastructure inadequacy. Although some natural resources, such as diamonds and gold, can be transported for refining and to markets by air, others (for example base metals) must be transported by land. This reality makes road networks in the territories crucial to the business case for current mines. New roads are required to develop new mining sites.

Table 2 shows the level of development of critical infrastructure in the Yukon, Northwest Territories, and Nunavut. It is clear from Table 2 that the infrastructure problem is most serious in Nunavut. Nunavut does not have any roads, relies on satellite for communication connectivity, and is dependent solely upon diesel for its power generation.

As a result of the infrastructure gap, many resources remain untapped in the territories because the cost of exploiting these resources is very high, and current market conditions (demand and price of the natural resources) do not make the exploitation of such commodities economically viable.

The existence of this infrastructure gap in the territories has meant that only big mining players with substantial

TABLE 2. Level of development of critical infrastructure in the Yukon, Northwest Territories, and Nunavut.

Infrastructure	Yukon	Northwest Territories	Nunavut
Power generation	Well-developed grid, largely powered by hydro.	Electricity grid around Yellowknife but largely diesel generated.	Small diesel generators provide power for each community.
Roads/Ports	Relatively large road network. No ports, but mining companies are considering ways of accessing Skagway in Alaska.	Limited all-season road network supplemented by winter ice roads. No coastal ports but tide-based ports (Tuktoyaktuk, Sachs Harbour, Ulukhaktok, and Paulatuk).	Nunavut Communities accessible by air only. Small craft harbour in Pangnirtung became operational in 2013. Landing areas of lower standard for sea lifts. Private access roads linked to specific developments at risk of being decommissioned unless new use/user can be found to operate and maintain them.
Connectivity	All but one community served by land-based services. Most established infrastructure in the territories.	A mix of land-based and satellite-served communities. Yellowknife has the best communication access among communities in the Northwest Territories. Mackenzie Valley fibre optic link in feasibility stage.	All 25 communities rely on satellite services. Many government departments rely on paper-based methods of communication.

Note: Source: Aboriginal Affairs and Northern Development Canada for Infrastructure Canada: Building for Prosperity, Canada's Long term Infrastructure Plan. Report of the Steering Committee, September 2012.

financial resources venture into the mineral exploration in this region. Some of the big mining companies currently engaged in mining activities in this region include Arcelomittal, AREVA, and Minerals and Metals Group. In some cases, even these big mining companies are reluctant to single-handedly shoulder the financial risks of mineral exploitation and withdraw from proposed mining projects. Consequently, it may be necessary to develop innovative financing options to support the development of public benefit infrastructure, aimed at opening up the economic potential of the territories.

In the absence of creative financing solutions, key infrastructure gaps will not be addressed and investments will not be made to exploit the natural resources, thereby impacting the demand for SMRs in this region.

3.3. Demand and price for commodities

In the long term, the exploration of the mineral resources in the northern territories will depend on the forecasted demand and price for the natural resources present in that region. The demand for these commodities depends on factors largely beyond the control of Canada. For example, the demand for iron ore (the key ingredient for steel making) is highly dependent on the trajectory of Chinese economic growth to a large extent. International iron ore prices are largely determined by Chinese demand, since China is the largest consumer of iron ore in the world [28]. Similarly, the prices of precious minerals such as gold and silver are influenced to a large extent by the international macroeconomic situation, particularly in the United States. For example, the demand for gold is influenced by the levels of gold reserves in central banks, prices of energy products, financial market indices, and global macroeconomic indicators such as economic growth rates, and the level of central banks' prime lending interest rates [29]. Higher levels of gold reserves exert a downward pressure on the price of gold, as will higher prime lending rates as holders of gold seek to sell their stocks to take advantage of the higher interest rates. At lower interest rates, gold is seen as a safe hedge of money [29].

Depressed metal prices significantly impact on global investment in mineral exploration, deposit appraisal, building of new mines, and refurbishment of existing mines. Currently, the global mining industry appears to be in a period of more cautious and disciplined capital spending. Some capital investments have been deferred due to low or fluctuating commodity prices, significant capital cost escalation, and a volatile global economic environment [30].

Consequently, the cyclical nature of the prices of natural resources found in the territories is seen as a significant barrier to developing the natural resources of the territories. The uncertainty related to the "boom and bust" nature of the demand for these commodities will not help the growth of exploration activities in the territories.

3.4. Availability of skilled labour in the territories

The shortage of skilled workers is felt throughout Canada [31], but the effects are particularly severe in the territories due to factors such as the high cost of living, lack of housing, distances from major urban centres, and lack of infrastructure. Consequently, the availability of skilled labor for the operation and maintenance of SMRs is a potential barrier to deployment of the technology.

A significant proportion of the territories' population is Aboriginal peoples, which is the fastest growing and youngest segment of Canada's population [32]. The large gap in educational attainment between Aboriginal and non-Aboriginal people in Canada has been well-documented [33]. For example, according to Statistics Canada [34], in 2011, almost one-half (48.4%) of Aboriginal people had a postsecondary qualification in 2011, including 9.8% with a university degree. In comparison, almost two-thirds (64.7%) of the non-Aboriginal population aged 25–64 years had a postsecondary qualification in 2011, including 26.5% with a university degree. Infrastructure challenges, social problems, and the proximity of educational institutions have culminated in the territories' populations generally lagging behind the rest of the country on educational attainment and adult skills.

Evidence suggests that a competitive labour market exists in northern/off-grid communities and that there is difficulty in enticing workers with utility experience to relocate to rural and remote communities [35]. There is also a difficulty for the northern/off-grid region of Canada to entice industry workers (with utility experience) without offering highly competitive wages due to its remoteness, lack of services, and extreme weather conditions. For example 10% of the employment positions at the Qulliq Energy Corporation (QEC) in Nunavut are vacant [36]. QEC faces the two-fold challenge of requiring highly skilled workers and the inability to pay competitive salaries compared with what is being offered in southern Canada. Other challenges that will be faced by operators of SMRs will be to develop a viable strategy to recruit and retain skilled employees to operate SMRs. The level and type of skilled employees demanded will depend on technical and regulatory requirements related to the type of SMR to be deployed.

3.5. Social acceptance

The deployment of SMRs in mines in the territories is likely to encounter concerns from the local population (or neighbouring communities) and anti-nuclear activist groups over the physical security of SMRs, radioactive waste management, and the perceived health and environmental effects of SMRs.

The issue of social acceptance of SMRs in the north is especially pertinent given that available evidence from other parts of the country suggests that Aboriginals (who form the majority of the population in this part of the country) are more likely than other Canadians to have a negative perception of nuclear power generation [37]. Although there is a lack of academic evidence on the perceptions of nuclear power generation among Aboriginals in the northern territories, it has been suggested that any successful deployment of SMRs in this region would have to be preceded by an effective trust-building consultation exercise with affected communities, from as early as the concept stage of the licensing process [38]. The consultation process should be tailored to recognize the unique needs and public acceptance priorities of each community [38].

It is also necessary for the nuclear industry to address the issue of management of spent fuel and other radioactive waste from the operation of SMRs. While nuclear batteries, a type of SMR, are envisioned to have features that allow for the replacement of the spent core either onsite or in a factory setting, the spent core still has to be stored somewhere (on site or somewhere else). Thus, while the issue of SMR waste may be different from conventional reactors, the waste problem is not totally eradicated. The issue of nuclear waste is key in enhancing the broader social acceptance of nuclear power generation.

3.6. Mines and legacy SMR issues

Currently, many mine operations are powered by onsite diesel-fueled generation, and there is no expectation of legacy assets remaining after mining operations cease. Once the mine is shut down, most of the associated equipment is removed. If SMRs are installed to provide energy and electricity for a given mining operation, the question arises about what to do with the SMR after mining operations cease. If these generation assets could extend the life and operation of the mine, or if the assets could be transferred to other industrial establishments that are in need of power, then that is an optimal solution. This issue of mine life and SMR legacy issues could have technical ramifications for SMRs concepts and designs. This could warrant the adoption of SMRs designs that require only one refueling timeframe that coincides with the average lifespan of a mine. To make this appealing, it is important for the cost of SMRs to be low enough to allow for the repayment of the full cost of the SMR within the lifespan of the mine. This requirement may impact the economics of SMR (demand for particular types and the cost of manufacturing of SMRs).

Another related issue is the cost of decommissioning SMRs that have been installed in remote sites. There is a need to maintain the access to the remote reactor site during decommissioning. This requirement places an additional cost on the mining concerns. This requirement may not be an issue if there are other active mining activities in the vicinity of the decommissioning site. However, if the decommissioning site is in a remote location then there is the problem of the additional cost of providing access to the site to satisfy regulatory requirements.

3.7. Regulatory challenges

The Canadian Nuclear Safety Commission has indicated that SMRs can be licensed with existing processes but additional requirements and guidance may have to be developed to deal with emerging technological approaches [39]. Some of the unique characteristics of SMRs are largely unstudied from a regulatory perspective and will require time for regulatory guidance. For example, safety claims about passive safety mitigation features of SMRs will need to be supported by strong research and development evidence derived from physical experiments and simulations [39].

Other aspects of SMR deployment in the territories that would require further regulatory research include emergency planning zones (which may be more complex in remote fly-in communities, where there may be nowhere to evacuate people to in times of emergency and air rescue may only be only possible weather permitting), transportable reactor cores, and remote operation of the facility [39].

Although regulations in Russia may be different from the Canadian framework, it is also important to point out SMRs have been operating in Russia for decades. The EGP-6 SMRs (12 MW_e) that were designed to operate in remote areas, severe climates, and permafrost conditions have been operated successfully since the mid-1970s [40] Thus, depending on the SMR technology in question, operational and other data may be available to vendors and the regulator to facilitate future licensing processes.

4. Discussion

A potential niche market exists for SMR deployment in mines in the territories. The introduction of Canadian-made SMRs, could also provide many socio-economic benefits to Canada. Some of these benefits include the creation of long-term, highly-skilled, high-income jobs for the Canadian economy and the provision of clean and reliable power for mining establishments in remote communities of the country. Having a reliable energy source for these activities will serve to expand social and economic activities in this region thereby reinforcing Canada's sovereignty over the Arctic region, part of which falls within the boundaries of the territories.

However, there are many technological, economic, political and social problems that need to be solved before the use of SMRs can become a reality in the North. These include: the uncertainty about the economics of SMRs, the infrastructure gap in territories as a disincentive to the exploitation of the mineral resources in the North, long-term demand for primary minerals (which is largely dependent on the world economic growth), and the social acceptance of nuclear power.

As discussed earlier, SMRs need to have a strong business case for the technology to be appealing to mining companies who could be among the early adopters of the technology. SMR vendors need to demonstrate that SMRs can be manufactured cost-effectively on a highly efficient production line. Although there is consensus that SMRs can only become competitive when there is mass production, a number of unanswered questions remain. What is the minimal number of SMRs needed to create a sufficient learning curve to overcome economies of scale? Who will place the first orders for SMRs? In view of the multitude of designs, how much demand exists for one particular SMR design? The exact cost of building an SMR cannot be estimated precisely until the “first of a kind (FOAK)” or lead plant engineering is complete and regulatory bodies have certified a design. Although it may be stating the obvious, the first few SMRs need to be deployed successfully, if more are to follow. These new reactors need be delivered on time and on budget (with adequate allowances for a FOAK build), to gain the confidence of potential early adopters in the private and public sectors. The cost of building and operating SMRs is still unknown; however, the front-loaded nature of the investments required for construction of SMRs means that confidence is key (whether from the private or government sectors) in motivating investments in SMR projects. This confidence will be dependent on the assessment of the financial risk assessments of SMRs. This is especially important given the important role of the government in being potential first adopters of SMR technology, as governments may be the only entities with the resources to absorb any financial risks associated with the initial introduction of SMRs.

The role of government in the provision of key infrastructure in the north is also very important in incentivizing the exploitation of natural resources in the north. Regardless of the infrastructure development funding formula developed, there is a need for a prominent government role in the provision of key infrastructure in this region of the country. Without this infrastructure the threshold for private investment in this region is elevated, reducing the likelihood that private firms will exploit the natural resources in this region.

Another area of government intervention could be in the form of a carbon tax on fossil fuels. Such a tax could make it more expensive for the use of fossil fuel energy sources, thereby promoting the use of SMRs. Although the likelihood of such a tax appears remote in the near future, this cannot be discounted in the long term.

The federal government could also help finance the construction of an SMR prototype for deployment in a Canadian Forces base in the Arctic. Such an undertaking would not only provide cogeneration capabilities for the military base, it would also contribute to a broader and robust SMR research and development program in Canada.

Although the available infrastructure could serve as an incentive, the long-term price and demand for primary commodities is an important factor that is beyond the control of Canada and highly dependent on the global growth especially in China, the United States, and Europe. Consequently, this is a factor that must be taken into consideration in assessing the potential of SMRs in the north.

As with any nuclear-related project, the issue of social acceptance is one that has to be tackled prior to the deployment of SMRs in the territories. Although there are no official statistics detailing the level of support for nuclear technology in the territories, evidence from other Canadian studies shows that Aboriginals (who make up the majority of people in the Territories) tend to have lower levels of social acceptance of nuclear technology compared with other Canadians. Given that the deployment of SMRs is more of a medium-term possibility (15–20 years), this is the time that the nuclear industry should be engaging in activities to enhance the social acceptance of nuclear technology in the north. It is also important to explore the institution of a new model of gaining social acceptance of nuclear technology. This model should involve a joint public outreach program by the nuclear industry, the government, the regulator, and other stakeholders in gaining social license for the technology in society.

It is clear that the various levels of governments in Canada have a significant role in making the deployment of SMRs in Canada and in the territories a reality. Although government intervention may not be the solution to overcoming all of the barriers to SMR deployment, it is clear that greater involvement and leadership by governments on this issue will assist the introduction of SMRs. This is especially true because the private sector appears to be unwilling to solely take on the financial risks attached to the deployment of SMRs. Government intervention may be in the form of playing a key role in the provision of critical infrastructure in the territories, providing incentives for the commercial manufacturing of SMRs (soft-loan guarantees and placing orders to be first adopters of the technology), and devising fiscal policies to promote clean energy.

5. Conclusion

Although the deployment of SMRs in Canada could potentially unlock many social and economic benefits for the country, there are important barriers to the deployment of SMRs in Canada that will need to be addressed.

What appears to be evident is that the deployment of SMRs in Canada is more likely to be successful with the support of all levels of government in the form of policies and actions. There will likely be a need for a coordinated approach by the federal, provincial, and territorial governments in facilitating the deployment of SMRs in this region. These governments should play key roles in not only assuming some of the initial financial risks related to the initial deployment of SMRs, but also in providing key infrastructure in this region to encourage mining exploration and exploitation activities.

SMR deployment will also raise social acceptance issues related to physical security, health, and environmental concerns. The introduction of the technology will encounter problems if the issue of social acceptance is not tackled successfully and in a timely manner.

Ultimately, regardless of what is done by governments and the nuclear industry, the deployment of SMRs in mines in the territories depends largely on the economic viability of exploiting the natural resources in this region. The boom and bust nature of the demand for the natural resources in this region creates a high degree of uncertainty in investors' plans to exploit the mineral wealth in this region, thereby creating market uncertainty regarding the demand for SMRs for mining operations in this region. However, this should not be a deterrent to SMR manufacturing because the argument can be made that the introduction of the technology facilitates the use of nuclear power in market niches such as developing countries with smaller electric grids, other remote locations, water desalination, and industrial heat supply.

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