SMALL MODULAR REACTORS (SMRs) – THE WAY FORWARD FOR THE NUCLEAR INDUSTRY IN CANADA?

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Abstract

Small Modular Reactors (SMRs) are being touted as safer, more cost effective and more flexible than traditional nuclear power plants (NPPs). 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 suitability of SMRs for various niche market applications in Canada. The paper examines the potential role of SMRs in providing an opportunity for remote mines and communities in northern Canada to reduce their vulnerability and dependence on costly, high-carbon diesel fuel. Other niche market applications of SMRs explored include: SMRs deployment in Saskatchewan for grid augmentation and as replacement options for Saskatchewan's ageing coal plants; the use of SMRs for bitumen extraction in the Oil Sands, and the potential use of SMRs in Canadian-owned foreign based mines. The socio-economic benefits of SMR deployments are also discussed. 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 technical, economic and social barriers that could impede the successful introduction of SMRs in Canada.

Introduction

Proponents of Small Modular Reactors (SMRs) argue that these reactors are the potential solution to the problems faced by larger traditional nuclear power plants (NPP), particularly soaring costs, safety, and radioactive waste management. Apart from the inherent qualities of SMRs noted above, proponents also point to the potential economic and social benefits of introducing SMRs.

In Canada, the deployment of small modular reactors (SMRs) may provide an opportunity for communities and businesses in northern Canada to reduce their vulnerability and dependence on costly, high-carbon diesel fuel. Boosting economic activity in the Arctic could also strengthen Canada's sovereignty over the region. Other potential benefits include job creation, income from export of the technology, and reduction of pollution from the exploitation of oil sands utilising SMRs for bitumen extraction.

The successful deployment of SMRs in Canada could be impeded by many issues. These include technical, economic and social issues related to the construction of SMRs that are suitable for the niche markets in Northern Canada, and the oil sands; the lack of uranium enrichment facilities in Canada; and issues pertaining to the social acceptance of nuclear power generation. Drawing on previously published literature, this paper nevertheless argues that the ideal conditions exist to support a vibrant SMR industry in Canada.

SMRs are defined by the International Atomic Energy Agency (IAEA) as reactors producing less than 300 MW_e of electrical power [1]. Given the variety of niche markets for SMRs in Canada, in this paper, micro-SMRs are defined as reactors generating 25 megawatts electricity (MW_e) or less and those generating between 150 and 300 MW_e. While 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.

SMRs are being marketed as having two general classes of applications. The first class is their applicability to niche markets in remote or isolated areas where large generating capacities are not needed, the electrical grids are poorly developed or absent, and where non-electrical products (heat or desalinated water) are as important as the electricity, e.g. in the Arctic regions in Canada, Russia, and the United States. The second class is the traditional on-grid deployment and direct competition for electricity production with large NPP and other sources of power. While this paper explores both classes of use of SMRs, the main focus will be on deployment of SMRs in off-grid locations, with a brief discussion of SMRs potentially replacing smaller coal-fired power generation plants in Saskatchewan.

While SMRs can be used for a variety of purposes, this paper focuses on SMR use for electricity generation in mining, households and in Steam-Assisted Gravity Drainage (SAGD) operations in the oil and gas sector [2].

The organization of this paper is as follows: Section 2 discusses SMRs and potential mining markets in the Northern Territories of Canada (e.g, Yukon, Northwest Territories, Nunavut) and in Saskatchewan. A discussion on the suitability of SMRs to meet the power needs of off-grid communities in the Northern territories of Canada is presented in Section 3, followed by an analysis of the use of SMRs in Oil Sands operations in Section 4. Section 5 outlines some of the potential contribution of an SMR industry to the nuclear value chain in Canada, followed by a discussion of the main barriers to the deployment of SMRs in Canada in Section 6. Section 7 provides concluding statements on the topic.

1. SMRs and Potential Mining Markets

Mines are large consumers of power, and can be a driving force for the expansion of electricity generation capacity. Adding a new mine to an electrical grid (if one exists in the locality of the mining) can impose a huge burden on existing infrastructure, and may require new electricity generation capacity. Some mines have negotiated power supply agreements with utilities to meet their power needs, while others have opted to generate their own electricity because it is cheaper, or because their mining operations are in off-grid locations.

SMRs have been touted as an energy solution for remote off-grid mining locations in Canada. This first part of this section discusses the opportunities for the deployment of SMRs in off-grid mining locations in the Northern territories, where the use of natural gas (NG) is not feasible and the main source of energy for industrial activities is diesel fuel. The second part of this section discusses the potential mining markets for SMRs in Saskatchewan. Potential foreign mining markets for SMRs are then briefly discussed in the last part of this section. This section does not discuss SMR operations for the Oil Sands mining operations as this topic will be discussed in a dedicated section later in the paper.

The mining[1] industry[2] is an important part of Canada's economy, contributing $52.6 billion to Gross Domestic Product (GDP) in 2012, while employing 418,000 workers in 1,264 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 twenty-five years. According to the Conference Board of Canada [4], the production of metallic and non-metallic minerals from the Northern part of Canada[3] is expected to grow by 91 per cent from 2011 to 2020, with a compound annual growth rate of 7.5 per cent. This growth in output would lead to a doubling of the value of Northern metallic and non-metallic mineral output, from $4.4 billion in 2011-12 to $8.5 billion in 2020.

In order for Canada to realize the benefits from the exploitation of the rich natural resource potential in the North, there is a need for access to reliable, environmentally responsible and comparatively low-cost energy sources. Given the vast size of Canada's northern region, 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 and infrastructure costs in the Territories tend to be relatively higher compared to 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 [5].

Lack of access to power is creating a significant barrier to resource development projects in Canada's territories. 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 generators create air pollution and greenhouse gases (GHGs) emissions, and expose industrial establishments to financial risks and instability through fluctuations in diesel fuel prices, high fuel transportation costs, and high maintenance costs. For example, in the Northwest Territories (NWT), diesel electric power generation costs, which include the diesel generators, fuel handling, and fuel storage, account for between 10% to 30% of the capital costs of a new mine [6]. NWT Power, the main electric utility in NWT, estimates that, for start-up mines in the territory, the cost of diesel generation includes an average annual operating & maintenance costs of $5.3M, and an

[1] Mining here refers to both metal and non metal mining activities.
[2] This refers to mineral extraction, smelting, fabrication and manufacturing activities related to metallic and non metallic 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)

annual average fuel cost of $27M [6]. 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 three diamond mines in the NWT spend between $15 and $20 million to construct seasonal roads annually [7]. 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 [6]. 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, if possible, at a lower cost than diesel power generation, can improve the business case for a mine under development or to extend the life of an operating mine. Given these conditions, it is clear that a potential niche market exists for SMRs in remote off-grid mining locations in the Territories. Further research on the competitiveness of SMRs in the Territories should be conducted in order to throw more light on viable energy options. While a strong business case for SMRs in mines in the Territories is important for commercialisation reasons, the use of SMRs in remote mines in the Territories may not only hinge on the economic competitiveness of these modules. SMRs could provide a more reliable source of power supply to mines, thereby alleviating the added burden of shipping and storage of diesel fuel during the short window shipping period in the North.

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 two diesel power plants, which provide a total 40MW of capacity [7]. According to NWT Power (the electric utility in the Northwest Territories), a typical off-grid diesel powered mine in NWT has an electrical load averaging 10 MW_e [6]. NWT Power estimates that currently proposed mines in NWT will require at least an additional capacity of 100 MW_e of new installed capacity [6], while Yukon Power (the electric utility in the Yukon) [8] 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$_)$. According to Table 1, currently proposed mines in Nunavut will require additional power capacity ranging from 150-200 mw_e. Given that currently, Nunavut's electricity base load is entirely provided by diesel generation, these proposed mines could be potential markets for SMRs. Approximately $160 billion worth of mining-related projects have been proposed for Canada (with many of these in the northern territories) in the coming years [3] and these projects are all potential markets for SMRs.

Table 1
Estimated Power Capacity of Existing and Potential Mines in the Northwest Territory, the Yukon and Nunavut[4]

Mining Projects	Capacity (MW)
NWT Projects	
Diavik	40
Ekati	15
Snap Lake	15
Sea Bridge Courageous Lake *	30 [9]
Canadian Zinc*	7.5 [10]
Avalon Thor Lake*	10
Gahcho Kue*	10
NICO*	15
Yellowknife Gold*	10
Nunavut Projects	
Meadowbank	26 [11]
Meliadine*	25.6 [12]
Hackett River*	25 [13]
Izok Lake*	5 [14]
High Lake*	10.5 [14]
Roche Bay*	30-50 [15]
Back River*	10-20 [16]
Kiggavik*	22 [17]
Mary River	
Yukon Projects	
Mactung Mine Project	*10 [18]*
Casino*	*150 [19]*
Selwyn Resources*	*35 [18]*
Eagle Gold	*5 [18]*
Ketza	*5 [20]*
Sources:[7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20] *: Refers to a proposed mining project	

[4] This list of proposed mines in the Territories is just for illustrative purposes and may not be an exhaustive list.

1.1 Economic Development, Arctic Sovereignty and SMR Deployment

Although Canada's sovereignty over its Arctic lands and Islands is undisputed (with the exception of the Danish claim over Hans Island) [21], as conditions in the Arctic become favorable for the exploitation of natural resources, it has become necessary for Canada to maintain a strong presence in that region.

One of Canada's strategies to exercise Canada's Arctic sovereignty is to promote sustainable social and economic development in the North [21]. The federal government's geo-mapping exercise for energy and minerals in the north could lead to more private sector industrial activities, thereby creating more jobs for northerners. The deployment of SMRs in mining and other industrial activities in the territories could provide the reliable and clean energy supplies needed to achieve economic growth in this region of the country. Increased economic activity in particular and Canadian presence in general in the Arctic region could go a long way in asserting Canada's sovereignty over this resource rich region, which will increasingly be the focus of international economic interests.

1.2 Potential Mining Markets in Saskatchewan

In Saskatchewan, expansion of the oil, gas, potash and uranium industries is expected to significantly increase electricity consumption. Increased demand for electricity coupled with the looming retirement of coal plants in the province provides an avenue for the deployment of SMRs. The provincial utility, SaskPower forecasts that even with conservation, it will need to rebuild, replace or acquire 4,100 MW_e of capacity by 2030 [22]. Current growth in electricity demand in Saskatchewan is increasing at a rate of approximately 110 MW per year [22].

Canada is a leading uranium producer and also has the world's largest reserves of high-grade, low-cost uranium ore, located mostly in northern Saskatchewan [23]. There are seven uranium mines in Saskatchewan; two are currently operating (including McArthur River which has the largest and highest-grade uranium ore deposit in the world), two have ceased mining operations but remain active milling sites, two are in development and will begin production shortly, and another that has initiated the decommissioning and reclamation process [24]. These mines currently have an average maximum electricity demand of 10 MW_e per mine. A forecast from SaskPower suggests that the electrical power demand for uranium mining operations in Saskatchewan will more than double by 2025, therefore approximately 60 MW_e must be added to the grid meet demand [25]. Currently, all uranium mines are connected to the provincial power grid in Saskatchewan; however, frequent extreme-weather events make service unreliable across the long distance transmission lines. Therefore, all uranium mines must maintain sufficient backup power to ensure continuous operation (24 hours per day, 7 days per week) and to ensure worker safety. SMRs could be used as incremental capacity to provide power to these mines.

Saskatchewan also hosts nearly one half of the world's proven potash reserves and the province consistently accounts for about one-third of global production [26]. In 2013, potash (a raw material used in the manufacture of synthetic fertilizers) was the most valuable product commodity by value of production ($6B) [26] in Canada. There is a large variation in the size and extraction process used by potash mines, resulting in some mines requiring as little as 35 MW_e of electricity, while others demand as much as 90 MW_e [25]. For the purpose of this paper, it will be assumed that a mine producing 1,000 kilotonnes (10^9 kg) of potash per year requires 60 MW_e of electricity. Between 2008 and 2028 mining companies in Saskatchewan plan to invest over $50B in new projects, and with an annual growth forecast of 5.3% [27], production will increase by approximately 11,670 kilotonnes/year, requiring an additional 700 MW_e by the year 2025. This increase in electricity demand could be met with the deployment of SMRs.

While many of these uranium and potash mines are on the SaskPower grid, increased demand for electricity due to growth of mining activities and the looming retirement of coal-fired power plants creates a potential market for SMRs. SaskPower currently operates three coal-fired generating stations that provide 1,682 MW_e of baseload capacity for the system, accounting for about 40% of SaskPower's annual power production [28]. These stations are [28]:

a. Boundary Dam Power station comprising of six units, with a total net generating capacity of 824 MW_e. Units one and two generating capacity of 62 MW_e and 61 MW_e, Units three, four, and five with generating capacity of 139 MW_e each, and unit six with a generating capacity of 284 MW_e. The retirement date for the plant is expected to be in 2025.

b. Poplar River Power station comprising of two 291 MW_e units has a total net generating capacity of 582 MW_e and the retirement date is expected to be between 2026 and 2028.

c. The Shand Power station consists of one 276 MW_e unit and the retirement date is expected to be 2038.

Based on the information above, it is clear that SaskPower's current grid structure would favor the deployment of SMRs (60 to 300 MW_e) when the coal-fired plants are retired. It is worth noting that Saskatchewan is also a province that not only plays a very important role in the current nuclear supply chain in Canada , but also has a relatively high public acceptance of nuclear power (with 66% of its residents supporting nuclear power generation [29]). Hence the possibility of SMRs replacing aging coal-fired plants is one that should be actively explored.

1.3 Foreign Mines as Potential Markets for SMRs

Canadian-owned mines in other countries are also potential markets for "made in Canada" SMRs. More than 800 Canadian companies are actively engaged in mineral exploration outside Canada in over 100 countries. Canadian firms account for the largest share of mineral exploration spending in Canada, the United States, Central and South America, Europe and, most recently, Africa [3].

As of 2010, over 1,000 Canadian mining companies owned assets abroad valued at over $129 billion in 100 countries. Almost half (48%) of Canada's mining assets abroad (CMAA) are located in four countries: Chile (14%); Mexico (13%); the United States (12%); and Argentina (9%) [30].

With the exception of Chile, all these countries have experience and expertise in nuclear power generation. Consequently, with the offer of incentives such as loan guarantees and tax breaks, Canadian mining companies could be encouraged to use Canadian-made SMRs to supply the energy needs of their mines in other parts of the world. Canadian government support may be needed to forestall any protectionist move on the part of countries to compel these Canadian companies to buy SMR modules from homegrown SMR vendors. For example, Argentina may want to see its own SMR (e.g. CAREM), used instead of a foreign-designed reactor. Similarly, the U.S.A. may prefer to see a SMR from one of its own domestic suppliers (e.g., NuScale, Hyperion, B&W, Westinghouse, etc.) selected instead.

2. Powering Off-grid Communities in Northern Canada

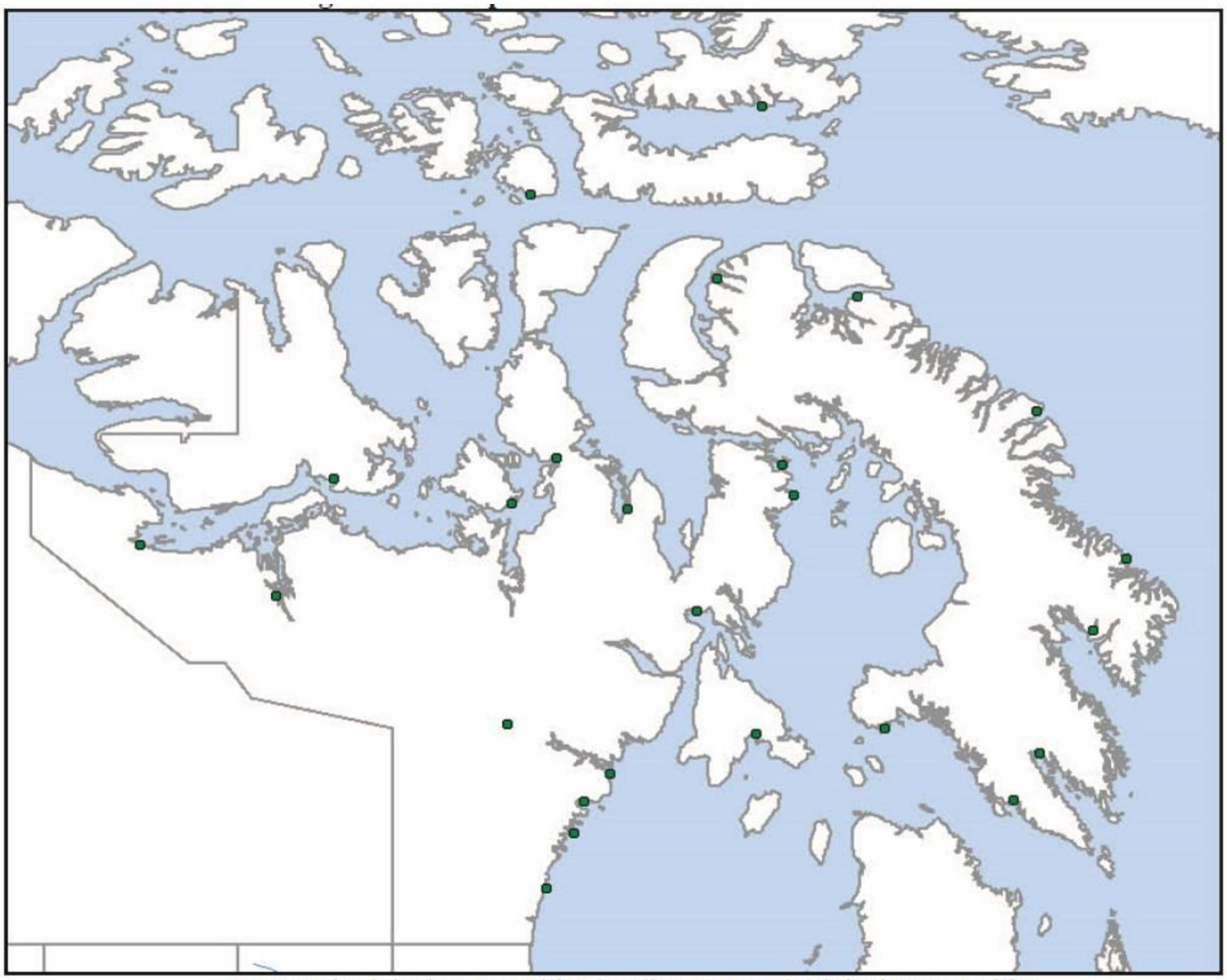
With a population of just over 100,000 (about 0.3% of Canada's population), dispersed over 3.5 million square kilometres, the Territories account for only 0.3% of Canada's total energy use. However, the per capita energy use is almost twice the Canadian average [5].

The Northern region also encompasses the Canadian Arctic[5]. Given the climatic conditions, and the dispersed nature of settlements in this region, the cost and reliability of energy production and distribution are important issues. Electricity costs in some northern communities are several times higher than the Canadian average on a per kilowatt-hour basis. For example, the average unsubsidized price of electricity is as high as 90.74 cents per kWh after subsidy in northernmost communities in the Arctic [31].

Population distribution within the Territories is clustered in several medium-sized cities, small mining towns, ice road communities and fly-in communities. Hydraulic generation ("Hydro" in colloquial terms) is the largest source of electricity generation for the Northern Territories as a whole (although Nunavut base load is 100 per cent diesel-generated electricity); however, the distribution network is limited. There are approximately 86 off-grid[6] communities in the Territories, with approximately 101,579 people living in them [32]. There are 5 diesel-powered communities in the Yukon, 26 in the Northwest Territories, and 25 in Nunavut, creating a total of 56 potential sites for SMR deployment, many of which are widely dispersed from each other [32]. In Nunavut for example, because all the communities have significant distances between one another, there is no local electricity grid [32]. Figure 1 below exemplifies the extent of the distances between settlements in Nunavut.

[5] The southernmost limit of arctic regions has commonly been placed at latitude 66 degrees, 32 minutes North. This latitude is considered the Arctic circle where the sun will not set on the date of the summer solstice and will not rise on the date of the winter solstice. In addition, this region is also north of the tree line, and is located where the average daily summer temperature does not exceed 10°C [14].

[6] An off-grid community, as defined by Natural Resources Canada, is a community that is neither connected to the North American electrical grid nor to the piped natural gas network; it is permanent or long-term (5 years or more), and the settlements have at least 10 permanent buildings.



Green: Aboriginal communities / Yellow: Non-Aboriginal communities

Figure 1 Map of Nunavut's Remote Off-grid Communities

Source: Aboriginal Affairs and Northern Development Canada [32]

Currently, a typical off-grid community relies on a diesel generator with an average capacity of 1 MW_e [33]. This is significantly less than the power required by industrial applications, thus it will be difficult to apply a single VSMR technology for industrial use and to supply power to households. A much smaller reactor, closer to the demand of approximately 1 MW_e, would need to be developed to meet the current energy requirements for these communities. VSMRs are technically feasible and Canada once was a leader in this field with AECL's SES-10 & Nuclear Battery programs. Another significant factor is that an economic analysis in 1988 found that nuclear batteries (a type of VSMR) were competitive with diesel fuel at $0.2/kWh [34]. Therefore, an updated re-assessment should be performed to re-affirm the validity of that result under current economic circumstances. However, it is also important to point out that economics should not be the only factor in deploying SMRs in these communities. The winter temperatures routinely drop below -20 degrees Celsius, and ironically, many homes in this region are heated with electricity, rather than using fuel oil directly for home heating. Consequently, the need for uninterrupted energy supply during winter conditions is of paramount importance. An interruption in power supply may make an emergency evacuation necessary (weather permitting). This dependence and vulnerability creates unique energy reliability requirements. SMR technology is a good candidate for both providing energy independence and a reliable district heating source to residents in the North because SMRs would significantly reduce the need to transport diesel fuel to the community, and would also eliminate concerns regarding the need for storing additional fuel in winter months when access to the communities is limited or impossible.

In spite of the their potential advantages, the deployment of SMRs in off-grid Northern communities is not likely to occur in the near future, given the current technical, sociological and political barriers such an introduction must initially surmount. First, there is the issue of the technological readiness of SMR concepts and designs suitable for the low-power demand required for these communities. Many of the SMR concepts and designs under consideration for near-term deployment have higher power output than the 1-MW_e average power supply required for average off-grid community in the North. The few SMR concepts that are close to the power range required to supply electricity to these Northern communities involve the use of less conventional technologies such as molten salt and gas cooled SMR technology that may take a relatively long time to be licensed because of the need for additional R&D required to satisfy regulatory requirements. Second, there is the issue of the economic viability of VSMRs. The question is open about what are the commercialization prospects of such small reactors that are potentially more expensive, both on the capital costs (cost per installed MW_e), and the production costs (cost per kWhr generated), in comparison with alternative technologies. Third, the availability of skilled labor for the operation and maintenance of these plants is a barrier to deployment. The large gap in educational attainment between Aboriginal/First Nations and non-Aboriginal people in Canada has been well-documented [35]. For example, in 2006, only 7.7% of Aboriginals had a university degree, compared to 24.3% of the non Aboriginal population [35]. Aboriginals have a lower participation and employment rates in the labour market. All of these characteristics are highly manifested in the labour markets in the Territories. This situation increases the likelihood of scarcity of skilled labour required for the operation and maintenance of SMRs.

3. SAGD Operations and SMRs

Alberta's proven oil reserves are approximately 170 billion barrels (with approximately 168 billion barrels in the oil sands), or approximately 13 per cent of total global oil reserves [36]. The oil sands deposits in Canada are a major source of bitumen and unlike conventional oil, bitumen is too viscous to pump to the surface. The two general classes of oil sands recovery are surface mining and *in situ* method. In open-pit mining, the oil sands ore is recovered above ground with heavy-ton trucks and electric or hydraulic shovels. The ore is then sent through an extraction plant where the bitumen is separated from the other components of the oil sands. For *in situ* methods, however, most of the bitumen is separated from the oil sands underground by thermal means (by heating up the oil sands to reduce the viscosity of the bitumen, enabling it to be pumped). The bitumen is then pumped to the surface for further processing. The oil sands industry faces challenges in finding ways to recover the bitumen from the oil sands and also in upgrading the bitumen to higher-quality oil

[37]. Approximately 80% of the deposits in Canada are too deep for surface mining and can only be recovered by *in situ* methods [36].

Various studies have confirmed the technical feasibility of integrating SMRs with Steam-Assisted Gravity Drainage (SAGD) operations, an oil extraction technology currently used in Canadian oil sands projects [38, 39, 40]. Analyses of the economic viability of such a deployment have generated mixed results, depending on the assumptions that are made regarding the long term competitiveness of SMRs against natural gas power generation (which is the dominant source of energy supply for SAGD operations) [2, 41].

SMRs have been proposed for three different functions in the oil sands. These include: (1) the production of high-pressure steam to heat up the underground deposits, inducing bitumen flow from SAGD mines, (2) the provision of electricity to the mines; and (3) the generation of electricity to produce hydrogen from water electrolysis. The hydrogen is then used to "upgrade" bitumen into a product similar to conventional crude oil. In both mining and *in situ* operations, the majority of the thermal energy required is used to heat and extract the bitumen. While both mining and *in situ* projects have large energy requirements for site operations and process heat requirements, analyses suggests that in situ bitumen extraction process provides an excellent potential market for SMRs.

According to the Canadian Association of Petroleum Producers (CAPP) [42], Oil Sands production is expected to increase from 1.9 million barrels per day (bbl/d) in 2013 (of these volumes, 1.1 million bbl/d were recovered by in situ techniques) to 4.8 million bbl/d (3.84 million bbl/d to be recovered using in situ techniques), an average annual growth of over 225,000 bbl/d through to 2030. The energy requirements for a SAGD plant are a function of the quality of the oil sands field, the *in situ* project, whether or not upgrading facilities are part of the suite of facilities, and the number of bbl/d produced. Current methods require on average approximately 20 MW_e of electricity and 150 MW_{th} of process heat in the form of high-temperature steam to produce 50,000 b/d of *in situ* bitumen [2]. Therefore, with an increase of over 2.7 million bbl/d, approximately 1,080 MW_e and 8,700 MW_{th} will be required to support production.

According to Bersak and Kadak at MIT [2], approximately 33.5 MW_e and 175 MW_{th} are required to mine and extract 50,000 bbl/d of bitumen using current mining techniques. Therefore, by 2030, with an increase of approximately 1 million bbl/d an additional capacity of 670 MW_e and 3,500 MW_{th} must be installed in Western Canada to support this increase in production.

The desire to increase oil production in the Athabasca Oil Sands region in Northeastern Alberta, and to do it economically while minimizing the impact on the environment illustrates the potential advantage of using nuclear power to meet the energy needs. Currently, natural gas is the most popular energy source used to generate the thermal energy and electricity required for SAGD operations. Natural gas-fired co-generation systems simultaneously produce electricity and thermal energy from a single facility, often using gas turbines with heat recovery steam generators. Such systems are becoming more popular because they are better suited for integrated SAGD and upgrading activities. A switch from NG co-generators to SMRs could decrease the sensitivity to the effects of fluctuations in the price of natural gas, as well as air pollution and greenhouse gas emissions produced in the bitumen extraction process.

The cost competitiveness of SMRs ($/MWh) as a replacement for natural gas-fired power facilities is dependent on factors such as the cost of natural gas, the cost of fuel for SMRs, government (both federal and provincial) policies on clean energy sources (such as a carbon tax). Projections from various sources state that for electricity production, nuclear energy becomes competitive with natural gas at a price of $7-$13 per million BTU [2, 41]. Projections for the price of gas show a slow rise in gas prices, with one estimate predicting that natural gas prices may not rise back above $7 (United States) per million BTU until around 2030 [2, 41]. While economic analyses examining the cost competitiveness of SMRs versus natural gas in the Oil Sands have produced varying results, it is worth mentioning that cost competiveness may not be the only factor impacting the integration of SMRs into SAGD operations. A significant concern about using natural gas in the extraction of oil sands is the magnitude of greenhouse gas emissions produced. These emissions limit Canada's effectiveness in lowering the country’s total emissions and could prove to be expensive for oil sands development companies, especially if a carbon tax is introduced. In addition, the cost competitiveness of SMRs with natural gas power generation may not be a barrier in certain cases if it is assumed that the VSMR application is in remote mine sites where there is no access to natural gas or an electrical grid.

Another issue that should be considered is that high-temperature steam from an SMR (or a natural gas-fired boiler) can only be transported by approximately ten kilometers (kms) by pipe [2]. Beyond ten kilometers, energy losses cause the steam temperature and pressure to drop below what is needed for the intended application. These additional requirements may impact the cost competitiveness of SMRs compared to using natural gas-fired boilers at locations closer to the application site. Despite these potential economic and technical shortcomings, SMRs could still be a good match with SAGD operations in the Oil Sands, provided the SMRs are located within 10 km of the application site.

4. SMR Deployment and Impact on the Nuclear Supply Chain in Canada

The nuclear industry supply chain in Canada currently employs approximately 30,000 Canadians, primarily in uranium mining and power generation operations [43]. Over 4,000 of these jobs are held by highly qualified personnel (HQP) who form an important part of Canada’s national innovation system, spanning over thirty universities and six major research centres including Atomic Energy of Canada Limited (AECL)[44]. Nuclear industry jobs are long-lasting (up to 50 years) and thousands of this industry’s HQPs and operators earn over $100,000 per year [43].

This section discusses some of the potential contribution of an SMR industry to the Canadian economy, primarily in the form of high-value jobs. The analysis in this section assumes that the deployment of SMRs will constitute an incremental installed nuclear capacity scenario as opposed to a replacement scenario for traditional large NPPs. Consequently, it is expected that the introduction of SMRs will create more highly-skilled, long-term and well-paid jobs for the Canadian economy.

Apart from providing a means of power supply for industrial ventures that could create thousands of jobs, an SMR industry could create jobs in all segments of the nuclear supply chain, including R&D, licensing/regulation, construction, manufacturing, reactor operations, fuel fabrication, fuel re-cycling, and decommissioning. SMRs have not yet been built on a commercial scale in North America or Western Europe. Consequently, no reliable estimates exist of the number of potential jobs that could be generated by an SMR industry. Important factors that could impact the number of jobs created by the manufacture of SMRs include:

a. Whether the SMR modules will be manufactured in Canada.

b. The number of modules to be constructed per year.

c. The percentage of the parts required for the SMR assembly plant will be sourced from Canada.

d. Whether SMR modules made in Canada will be exported.

Answers to these questions do not exist for now and may not be available for some time.

The operations of SMRs could also create many jobs. No matter how simplified the SMR design is, all plants will require highly trained operators and maintenance (O&M) personnel. In general, total staffing levels for SMRs are expected to be smaller than those for larger NPPs. However, staffing levels on a personnel/MW_e-installed basis are typically expected to be higher for SMRs than for the larger NPPs [45]. A wide variation of staffing levels is anticipated for the many new SMR designs, hence the number of possible O&M jobs created in Canada is dependent on the design of the modules and number of SMR modules produced and utilised in Canada. Given the expected closure of the Pickering NPP (~3,000 MW_e of installed capacity) in Ontario between 2018 and 2021, the deployment of SMRs to replace this baseload capacity could make up for some or all of the jobs that would be lost at the Pickering NPP after its shutdown. This scenario would be contingent on the time lapse between when the SMR industry is initiated and when the Pickering NPP is closed.

An SMR industry will also add jobs to other segments of the nuclear supply chain in Canada. The nuclear supply chain in Canada includes more than 200 private sector companies [44]. The companies in this specialized sector manufacture major components and specialized equipment for nuclear power stations and provide engineering and support services to the 20 operating CANDU nuclear power reactors in Canada as well as to CANDU and light water reactor (LWR) NPPs in other nations. While exact numbers are not known, the introduction of SMRs could potentially grow this supply chain to meet international SMR needs, thereby creating more jobs in Canada. While SMRs may make use of existing supply chain, the deployment of SMRs could also provide opportunities for expansion of supply chain beyond the traditional nuclear industry. The level of benefits accruing to the current nuclear supply chain will depend on the type of fuel used by a future SMRs in Canada, and the ability of companies to provide the necessary specialised equipment and services for a new fuel type.

Despite the uncertainty surrounding the economics of SMRs in Canada, 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. It could also lead to the creation of good jobs and could potentially propel Canada as a Centre of Excellence for SMR technology. In order to achieve these feats, a number of barriers to the deployment of SMRs have to be surmounted.

5. Barriers to the Deployment of SMRs

This section discusses some of the major barriers that have to be surmounted before SMRs can be successfully deployed in Canada. These barriers include:

(1) Commercial viability or economics of SMR deployment.

(2) Potential regulatory barriers due to the complexities related to First-of-a-Kind (FOAK) facilities and the deployment of SMRs to new niche markets (primarily remote Northern communities).

(3) Social acceptance issues particularly among Aboriginals.

(4) Technological readiness of SMRs with low power capacity suitable to match the power demand in Northern remote communities.

(5) Lack of required skills in Northern communities to operate and maintain SMRs.

5.1 Economic Viability of SMR Deployment

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:

(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 commercial success of SMRs. The demand for SMRs to supply power for extracting natural resources will also be influenced by the price 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 market size for SMRs is potentially tens to hundreds of units. However, given the variety of SMR designs on stream, how much demand exists for one type of SMR? A consolidation of SMR designs and vendors to increase market shares may be necessary to optimise demand.

(2) **Availability of Infrastructure**

The lack of critical infrastructure in the Territories could also impact economic activity in that region, thereby impacting the demand for SMRs. The lack of infrastructure such as all-season roads, ocean and waterway ports and railways required for the transport of equipment, and extracted mineral resources raises the cost of doing business in the Territories. This makes it less economically attractive to invest in these mining ventures. Consequently, many resources remain untapped in the Territories because the cost of exploiting these resources is very high, such that current market conditions do not make them viable to be exploited. A survey of Mining Companies by the Frasier Institute [46] 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.

(3) **Economies of Factory Production of SMR Module**

Researchers agree that for SMRs to be competitive, mass production is needed [47]. The ability of SMRs to be mass produced in factories and shipped to operation sites in order to reduce costs is said to be one of the main advantages of the technology [48]. For this feat to be achieved, SMRs need to be manufactured on a highly efficient production line.

(4) **Regulatory Requirements and Cost of SMRs**

SMRs using innovative technologies may require greater regulatory oversight which may increase the cost of production and operation of the modules

(5) **The cost of waste management and decommissioning**

Given the variety of SMRs designs under consideration, fuel waste management and decommissioning costs are uncertain. Consequently, any business case study on the commercial viability of SMRs must take waste management costs into account.

(6) **Government Policies on SMRs**

These policies could include incentives for first adopters, use of first-build SMRs on government facilities such as military bases, power purchase agreements, production tax credits, loan guarantees, clean energy policies such as carbon tax policy, and export policies.

5.2 SMRs and Residential Power Demand in Northern Communities

One of the barriers to successful deployment of SMRs is that many of the current SMR designs are over-sized for many of the niche market applications in Canada. For example, only a few of the currently available SMR concepts have proposed power levels within the range of the average level of power demand in household settlement communities in the North (please see table 2 below for a listing of SMR concepts, vendor, type, and power level). These SMR concepts are based on less conventional technologies (such as lead, sodium and gas cooled technology) with limited operational experience, relative to concepts based on LWR technology. These SMR concepts also have a relatively low technological readiness, and deployment prospects are expected to be delayed, while technological issues are addressed through R&D activities and prototype testing.

Table 2
Sampling of Available SMR Technologies [49]

		Country	Type	MW_{th}	MW_e	Fuel Cycle (a)	Temp. (°C)	Uranium Enrich (%)	Design Status
Micro-SMRs (,50MWth)	UNITHERM	Russia	PWR	20	2.5	25	330	19.75	Concept
	SHELF	Russia	PWR	28	6	4.5	320	UO_2 & Al	Concept
	4S	Japan	LMR	30	10	30	510	MOX	Detailed
	StarCore [50]	Canada	HTGR	30	10	5	750	TRISO	Concept
	ABV-6M	Russia	PWR	38	8.6	10	330	19.7	Development
	Sealer [51]	Sweden	LMR	8	3	30	450	UO_2 & 19.9	Concept
SMRs (50MW to 300MWth)	G4M	USA	LMR	70	25	10	500	19.75	Concept
	CAREM	Argentina	LWR	100	25	1.2	326	3.1	Detailed
	NuScale	USA	PWR	165	45	2	329	4.95	Detailed
Sources: [49, 50, 51]									

There is also the question of the ability of SMRs to follow load demand as it changes during daily, weekly, and seasonal cycles. Given the time-variation in power use in northern communities this issue is important to address. VSMR designs will have higher capital and operational costs per unit of kW_e generated and given the relatively low income in this part of the country, without government subsidies, this venture is less likely to be commercially viable. However, if the goal is to provide a clean and reliable source of energy to people in remote communities, then economics alone will not be the determinant of the deployment of SMRs in this region of the country.

5.3 Potential Regulatory Barriers

The Canadian Nuclear Safety Commission (CNSC) 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 [52]. For example, additional research may be needed for calculation of source-terms for novel designs based on non-water-cooled technologies, such as liquid-metal or gas-cooled reactors. New licensing requirements may also be required for FOAK SMR manufacturing plants.

Other aspects of SMR deployment that would require further regulatory research include emergency planning zones (which may be more complex in remote fly-in communities in the North, 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, onsite security and number of operating and maintenance staff.

5.4 Social Acceptance Issues

The deployment of SMRs is likely to encounter social acceptance issues. Public concerns over nuclear weapons proliferation, the physical security of SMRs, and health and environmental effects of SMRs could attract protests from the anti-nuclear activist groups. Low social acceptability may culminate in the “not-in-my-backyard” (NIMBY) sentiment in the public, and “not-in-my-term-of-office” (NIMTOO) sentiment among local elected officials. Such sentiments could ultimately lead key decision-makers to delay implementation actions on SMR deployment.

The issue of social acceptance is especially pertinent giving the much touted opportunities for SMR deployment in the Territories, where available evidence consistently suggests that Aboriginals / First Nations (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 [36]. As a result of these social acceptance issues, it would be important to devise an effective communication strategy to explain the benefits and relative risks of nuclear power to the Aboriginal community in the North. This strategy should also seek to balance issues related to Aboriginal support, energy use, and aboriginal land rights.

Another important social acceptance issue relates to nuclear weapons proliferation concerns. As low-enriched uranium (less than 20 wt% U-235/U) is a requirement for all of the currently proposed SMR designs, a careful navigation of the national and international politics of nuclear proliferation will be required in order to successfully enrich uranium for SMR modules. If this socio-political barrier is overcome, uranium enrichment could provide excellent opportunities to increase the value of Saskatchewan’s uranium exports and create high-value jobs.

6. Conclusion

The deployment of SMRs in Canada could potentially unlock many social and economic benefits for the country. On the economic level, SMRs could add value to Canada’s existing nuclear supply chain leading to the creation of highly skilled, well paid and long-lasting jobs. It could help revitalize nuclear R&D in universities and national laboratories and create the needed expertise that could propel Canadian firms to become global SMR suppliers, thereby creating more jobs and value added to the Canadian economy.

The introduction of SMRs into the North could also provide a reliable and economically competitive source of energy for mining and other industrial undertakings, with a reduced environmental impact relative to other forms of power generation. These industrial activities could provide further social and economic benefits for this part of the country. With the opening up of the Northern Passage, economic activities in the Arctic region are likely to increase. 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 region.

There are important barriers to the deployment of SMRs in Canada that will need to be addressed. One is the economics of SMR production. The cost of building and operating SMRs is still unknown. The level of demand or customer interest in these modules is also unknown. What is clear is that there will likely be a need for federal, provincial and territorial governments to shoulder some of the initial financial risks in the deployment of SMRs, before the private sector can assume 100% of the financial risks. Government policy in the form of power purchase agreements, loan guarantees, purchasing of SMRs for government installations and clean-energy policies will assist in promoting the SMR industry.

Another issue to address is that of the skills required for the regulation of these reactors. Depending on whether the SMR design is a more advanced type (such as a liquid-metal or gas-cooled designs) based on more conventional water-cooled designs (light water or heavy water), there may be a need for further R&D on ways of regulating the deployment of SMRs. Factory manufacture of SMR modules is a relatively new concept to the CNSC and this could potentially delay the SMR deployment process as new regulations have to be put in place to govern the operations of such a plant. Other regulatory barriers include emergency planning zones, the number of operating, maintenance and security staff on SMR site, the transportation of reactor cores and waste management and decommissioning costs.

SMR deployment will raise social acceptance issues related to nuclear weapons proliferation, physical security, health, and environmental concerns. This is particularly important given the proposition about introducing SMRs in the Territories, where the population is predominantly Aboriginal/First Nations, a demographic group that is known to be historically opposed to nuclear power generation. An effective communication strategy will be needed to explain the benefits and risks of nuclear power generation in a way that could garner the support of the aboriginal communities. A proper understanding of the economic and environmental benefits of nuclear power should help increase social acceptance of nuclear among Aboriginals.

The deployment of SMRs in Canada is more likely to be successful with the support of all levels of government in the form of supportive policies and actions. Given that Ontario and Saskatchewan are the most nuclear friendly provinces in Canada, the support of these two provincial governments, together with the federal government are pertinent in any plans to introduce SMRs in Canada.

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