

**Ontario Ministry of Energy
SMR Deployment Feasibility Study**

**Feasibility of the Potential Deployment of Small Modular Reactors
(SMRs) in Ontario**

Table of Contents

Disclaimer	5
Executive Summary	6
1. Introduction.....	14
1.1 Background.....	14
1.2 Historical SMRs in Remote Applications	15
2. Methodology	17
2.1 Methodology Overview	19
2.2 SMR Evaluation Tool Development.....	20
2.2.1 Technology Compatibility Assessment	20
2.2.2 Vendor Readiness Assessment.....	20
2.2.3 Technology Readiness Assessment.....	20
2.2.4 LCOE Calculation.....	21
2.3 SMR Evaluation Databank Development	21
2.3.1 SMR Design Selection	21
2.3.2 Design Specific Data.....	21
2.3.3 Generic Nuclear Data.....	22
2.3.4 Generic Non-Nuclear Data.....	22
2.4 Major Assumptions and Exclusions	22
3. Deployment Site Characteristics and Descriptions	24
3.1 General Description of Northern Ontario	24
3.2 Description of Off-grid Remote Mines in Northern Ontario.....	26
3.2.1 Current Status of the Ring of Fire	26
3.2.2 Prospective Mine Sites	26
3.2.3 Current Power Situation	28
3.2.4 Load characteristics	28
3.2.5 Generic Canadian Remote Mine Description	29
3.2.6 Special Conditions	32
4. Technology Suitability Evaluation Tool	35
4.1 Reference SMR and Criteria Development	35
4.2 Weighting Factors	39
4.3 Rankings	39
5. Technology Deployment Potential Evaluation Tools.....	40
5.1 Technology Readiness Levels (TRL).....	40
5.2 Vendor Readiness Levels (VRL)	44
6. Financial Evaluation Tool	46
6.1 Method	46

6.2	Financial Assumptions	46
6.3	Analysis Scenarios.....	47
6.4	LCOE Formula	47
6.5	Major Inputs	47
6.5.1	Capital expenditure	47
6.5.2	O&M Costs.....	48
6.5.3	Fuel Costs	48
6.5.4	Regulatory Costs.....	48
6.6	System Configurations.....	49
7.	Initial Values for SMR Evaluation Databank	50
7.1	Identification of SMRs and Initial Screening	50
7.1.1	Initial list of SMRs.....	50
7.1.2	Screening Criteria	50
7.1.3	Small Modular Reactor Shortlist	51
7.2	Design Specific Data	52
7.2.1	Technical Descriptions	53
7.2.2	CAPEX	54
7.3	Generic Data (Non-Nuclear)	54
7.3.1	GHG Emission	54
7.3.2	Long-Term Diesel Price	57
7.3.3	Diesel Engine Lifecycle Cost	58
7.3.4	Flywheel cost	58
7.3.5	Cost Escalation (CPI).....	58
7.3.6	Currency and Exchange Rate.....	58
7.4	Generic Data (Nuclear).....	59
7.4.1	Security Staff Complement	59
7.4.2	Additional Security Cost.....	62
7.4.3	Non-Proliferation Compliance	62
7.4.4	Staffing Complement Requirement.....	62
7.4.5	Decommissioning.....	66
7.4.6	Nuclear Fuel Waste Management	67
7.4.7	Fuel Cycle Cost.....	67
7.4.8	Spent Fuel Storage Cost.....	70
7.4.9	Insurance Cost	71
7.4.10	Licensing Cost.....	71
8.	Results.....	72
8.1	Technology Suitability Evaluation	72
8.2	Technology Deployment Potential Evaluation	72
8.2.1	Technology Readiness Level.....	72
8.2.2	Vendor Readiness Level	73
8.3	Financial.....	73
8.3.1	SMR Deployment Target Levelized Cost of Electricity	73
8.3.2	Discount Rate Sensitivity	74
8.3.3	LCOE Cost Components	75

9. Discussion	76
9.1 General	76
9.1.1 Regulatory Aspects of SMRs	76
9.1.2 Vendor Observations	76
9.2 Social Economic Impact	76
9.2.1 Methodology	77
9.2.2 Potential Market Sizes	78
9.2.3 Potential Economic Impacts	79
9.3 GHG Impact	80
9.3.1 Remote Mines	80
9.4 SMR Deployment Challenges and Recommendations	81
9.4.1 Challenges	81
9.4.2 Recommendations	82
9.5 Future Works and Path Forward	83
9.5.1 Refinement of the Current Study	83
9.5.2 Technology Selection Studies	83
9.5.3 Timelines	84
10. Conclusion	87
10.1 Major Findings	87
10.2 Potential SMR Benefits	88
10.3 Technology Selection	89

Disclaimer

This report was prepared by Hatch Ltd. ("Hatch") for the sole and exclusive benefit of the Ontario Ministry of Energy, the Client, for the purpose of discussing the progress of the study titled A Feasibility of the Potential Deployment of Small Modular Reactors (SMRs) in Ontario (the "Study"). Any use of this report by the Client is subject to the terms and conditions of the Agreement between Hatch and the Client dated 2 October 2015, including the limitations on liability set out therein. Any use of or reliance upon this report by any third parties is at the sole risk of such parties and Hatch disclaims any and all liability to any parties other than the Client in connection with this report.

This report is meant to be read as a whole, and sections should not be read or relied upon out of context.

The assumptions, technical calculations, cost estimates and economic analysis as presented in this report have been conducted to the intended accuracy level of a preliminary, high level study, and, accordingly, all data contained herein is based upon limited information available at the time of preparation. The quality of the information contained herein is consistent with the intended level of accuracy as set out in this report, as well as the circumstances and constraints under which this report was prepared.

This report contains the expression of the professional opinion of Hatch, and while the assumptions, information, calculations and estimates herein may be considered to be generally indicative of the result of the Study, they are not definitive. No representations or predictions are intended as to the results of future work, nor can there be any promises that the assumptions, estimates and projections in this report will be sustained in future work.

Executive Summary

Key Findings

From an initial list of ninety small modular nuclear reactor (SMR) technologies, nine designs (less than 25 MWe) were selected and short listed for detailed assessment for potential deployment in off-grid remote mines, with specific emphasis placed on northern Ontario. The technical readiness, vendor readiness, technology compatibility and lifecycle power costs of these reactors have been examined in detail. The results are as follows:

- All of the SMRs are expected to be economically competitive against the incumbent diesel energy source with potential power cost-savings up to \$152/MWh.
- SMRs can provide very low carbon power and meet the reliability requirements of mining operations which could accelerate the development of natural resources in remote locations (e.g., Ring of Fire in northern Ontario).
- The technology compatibility evaluation results indicate that a majority of the nine SMR designs in this study are highly compatible for remote applications, with the exception of one design that is primarily being developed for on-grid applications. This result has shown that the technology vendors reflected general site characteristics and conditions in developing the SMR design requirements.
- As most of the SMRs under consideration are in part based upon existing technology and knowledge, a majority of the nine SMRs considered fall in the range of medium levels of technology readiness. The vendor readiness evaluation shows that there are two distinct types of vendor in the SMR development industry; a group of established nuclear technology companies with technical and financial resources but with a fragmented interest in the SMR market, and a group of venture companies that lack resources but have a focused interest in the market.

In addition to technology specific feasibility analyses, the following key findings are produced:

- Greenhouse gas reduction potential: For Ring of Fire mining, 962 million (reference case) to 3 billion litres (high-demand case) of diesel consumption and 2.7 million to 8.3 million tonnes of CO₂ equivalent GHG emission can be avoided during a 20-year project lifetime. These are equivalent to removing 28,500 to 87,500 passenger cars from the road annually.
- Socio-economic impact to Ontario: Deployment of SMRs in remote Canadian and international communities and mining sites could have both direct and indirect impacts on Ontario's economy depending on the province's participation level within the nuclear industry in developing and manufacturing the technologies. Based on 50% participation in the manufacturing of SMRs, the impacts are estimated to be approximately \$4 billion and 20,000 employment-years in the case where SMRs can be fully deployed to potential

Canadian remote areas, with up to \$148 billion and 542,000 employment-years if SMRs can be exported to serve potential international remote communities and mines.

- **Challenges:** The major challenges in SMR development are the scarceness of cost-effective technology demonstration sites, qualified nuclear operators, and funding for the demonstration unit.

In addition to performing an analysis on remote mining applications of SMRs for the Ontario Ministry of Energy, Hatch also examined the applicability of this study on assessment of SMR deployment in remote mines and remote communities in northern Canada for Natural Resources Canada (NRCan).

While the key findings above for technology and vendor readiness of SMR designs for Ontario remote mines are applicable to Canada's northern remote mines and communities to a large extent, the key differences are as follows:

- Four SMR designs under 5 MWe out of the nine shortlisted SMRs are identified as potentially suitable designs for specific characteristics of remote communities¹ such as redundancy and reliability configurations, load following capability, and expected load growth.
- Three of the four SMRs for potential deployment in remote communities are expected to be economically competitive against the incumbent diesel energy source with potential power cost-savings up to \$187/MWh.

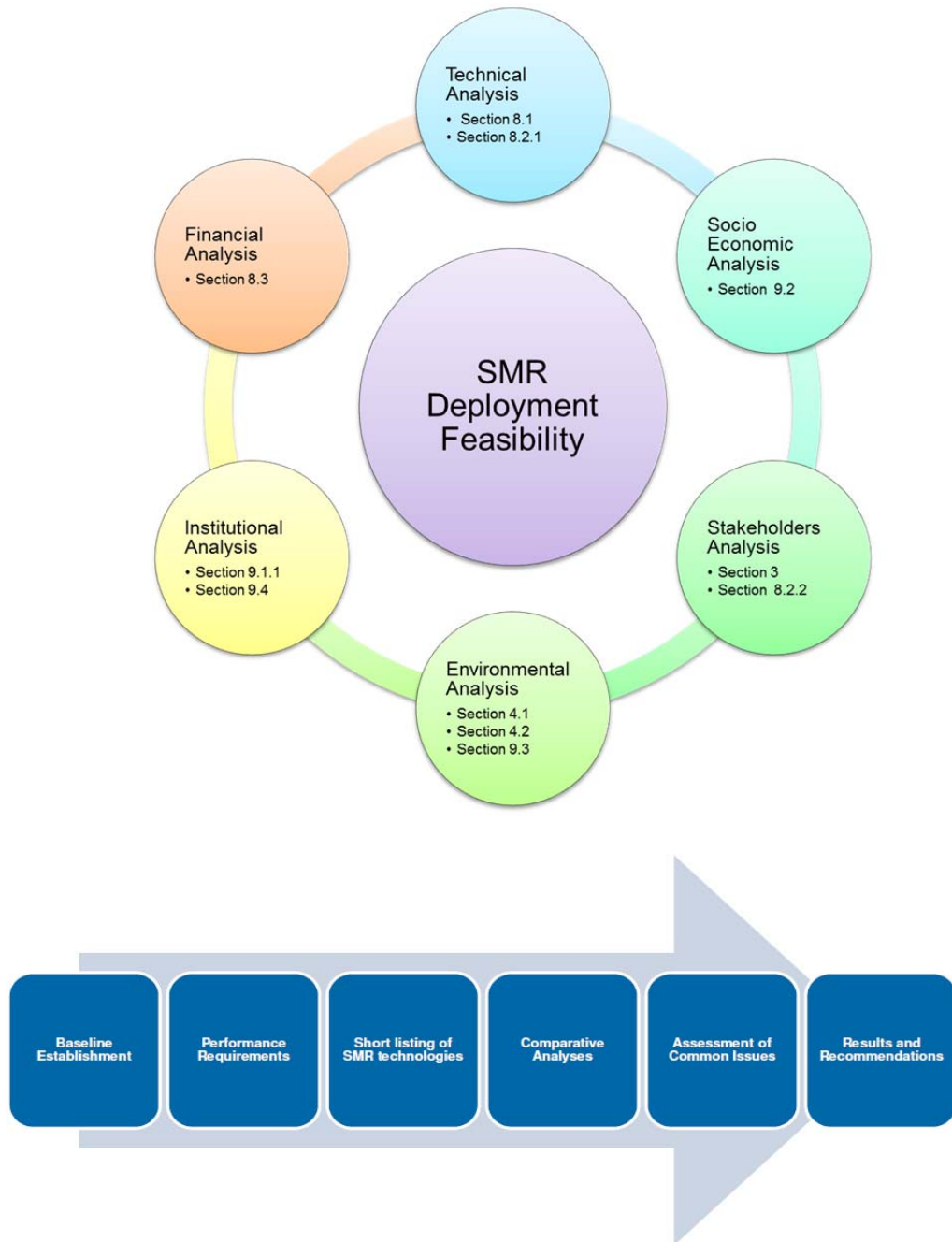
Objectives of the Study

The small nuclear reactor industry has recently been emerging in Canada and these vendors have been promoting SMRs as the potential power solutions for remote mines. This study aims to provide decision makers in Ontario and within the federal government with an assessment of the current state of SMRs against pre-determined criteria to properly assess the benefits and risks associated with the deployment of SMRs in Ontario for remote mines.

Study Overview and Methodology

The SMR deployment feasibility is a composite of the following six analyses; technical, financial, socio-economic, stakeholders, institutional and environmental. The report sections where these results can be found are shown in the diagram below.

¹ For illustrative purposes, Hatch examined off-grid communities in Northern Ontario based on available data from the former Ontario Power Authority (OPA), Aboriginal Affairs and Northern Development Canada (AANDC), and NRCan.



The study is performed by following the sequential process shown in the above diagram.

Hatch undertook a comparative analysis and assessment of the nine short-listed designs by using four tools:

1. **Technological Compatibility**

- To score each SMR technology for suitability for remote mine deployment considering factors such as operating characteristics, waste management, security, climate suitability, etc.

2. **Technology Readiness Level**

- To score each SMR technology for readiness of key components such as safety and control systems, reactor physics and fuel.

3. **Vendor Readiness Level**

- To score each SMR vendor for readiness considering factors such as corporate structure, financial resources, client engagement status, supply chain and regulatory approval status.

4. **Levelized Cost of Energy (LCOE) calculation**

- To calculate for each SMR technology the lifetime cost of energy (\$/MWh) considering capital costs, maintenance and labour, fuel and regulatory costs divided by total energy produced. (**Note:** Hatch used a 6% discount rate for the calculation.)

The inputs for these assessments included data specific to each design (e.g., vendor surveys), and generic nuclear and non-nuclear data from public sources as well as Hatch's in-house expertise.

Nine Shorted Listed SMR Technologies

As a result of Hatch's comparative analysis and assessment, the nine designs suitable for remote mines have been identified. The vendor and reactor names are not specified due to commercial confidentiality; however, their technology types are indicated as follows:

- Integral Pressurized Water Cooled Reactor 1 (IPWR-1)
- Integral Pressurized Water Cooled Reactor 2 (IPWR-2)
- Gas Cooled Reactor 1 (GCR-1)
- Gas Cooled Reactor 2 (GCR-2)
- Gas Cooled Reactor 3 (GCR-3)
- Lead Cooled Fast Reactor (LFR)
- Sodium Cooled Fast Reactor 1 (SFR-1)

- Sodium Cooled Fast Reactor 2 (SFR-2)
- Molten Salt Reactor (MSR)

Of the 9 shortlisted SMR designs, the four SMR designs (under 5MWe) suitable for northern remote communities application are as follows:

- Sodium Cooled Fast Reactor 1 (SFR-1)
- Lead Cooled Fast Reactor (LFR)
- Gas Cooled Reactor 2 (GCR-2)
- Gas Cooled Reactor 3 (GCR-3)

Technologies Ranking Based on Evaluation Criteria

For the remote mining application, no technology is identified as the best technology in all evaluations.

(1) Technology Compatibility

The technology compatibility evaluation result shows medium compatibility levels for the majority of the SMR designs for remote mining applications, with the exception of one design that is primarily being developed for on-grid application and scored low in the compatibility analysis.

This result indicates that the technology vendors reflected the site characteristics and conditions in developing the SMR design requirements for remote mining applications.

(2) Technology Readiness level (TRL)

Most SMRs are in medium levels of technology readiness (TRL) based on the technology maturity evaluation results.

The majority of technologies score between 4 and 7 (out of 9) in the TRL scales with only one technology scoring below 3 on average, where 1 means that basic principles are observed and 9 means that the technology is commercially available. The technology maturity qualitatively indicates what future R&D and development costs associated with the technology will be necessary before the technology can reach a licensable stage. Technologies with lower scores will incur additional development expenses than those with higher scores.

(3) Vendor Readiness

The vendor readiness evaluation (VRL) shows that there are two different groups in the SMR development industry; a group of established nuclear technology companies with technical and financial resources but with a fragmented interest in the smaller-scale off-grid SMR market, and a group of venture companies that lack resources but have a focused interest in

the market. Both groups scored low in terms of regulatory approval, client engagement, and stakeholder engagement, indicating that the SMR industry in Canada is still in a very early development stage.

Financial Analysis Results

The levelized costs of electricity (LCOE) for SMRs in remote mining applications have been analysed using a 6% discount rate. All technologies investigated in this study have shown to be competitive against diesel power generation technology.

Hatch LCOE calculation for continued diesel generation for remote mines is \$345/MWh, which is consistent with operating values in recent technical reports for northern Canadian remote mines.

The preliminary LCOE of the nine SMR technologies ranges from \$193/MWh to \$288/MWh, depending on specific technology and specific mining site application. This represents estimated potential savings of up to \$152/MWh for SMR deployment for remote mines compared to current diesel power generation.

The examination of the LCOE cost components reveals that the nuclear technology LCOE will be sensitive to capital costs, staffing, fuel costs, initial regulatory costs and carbon tax credits.

While the SMR economic competitiveness is only indicative because of many uncertainties in SMR input costs, the gap between diesel and SMR LCOE in combination with conservative cost values used in this study indicates that there is a significant margin for error in the economic competitiveness result.

For northern remote communities, Hatch's LCOE calculation for continued diesel generation for remote communities is \$647/MWh.

The preliminary LCOE of the three SMR technologies which are favourable to diesel ranges from \$460/MWh to \$543/MWh. This represents estimated potential savings of up to \$187/MWh for SMR deployment for remote communities compared to current diesel power generation. The fourth SMR design has a higher LCOE (\$788/MWh) than that for diesel generation due to higher capital costs.

Recommendations

As the prime sites and operators for an SMR demonstration project are all located in Ontario, the Government of Ontario can play a role in facilitating access to these resources for potential technology vendors. It is likely that the first mover will have significant advantage in securing the SMR market share.

Thus, Hatch recommends that Ontario consider a process by which a limited number of technologies can be supported during the demonstration phase, with emphasis on the potential benefit to Ontario which could include the technology vendor(s) based on their

potential contribution to Ontario's economy and supports the vendor(s) during the technology demonstration phase to become the first mover(s).

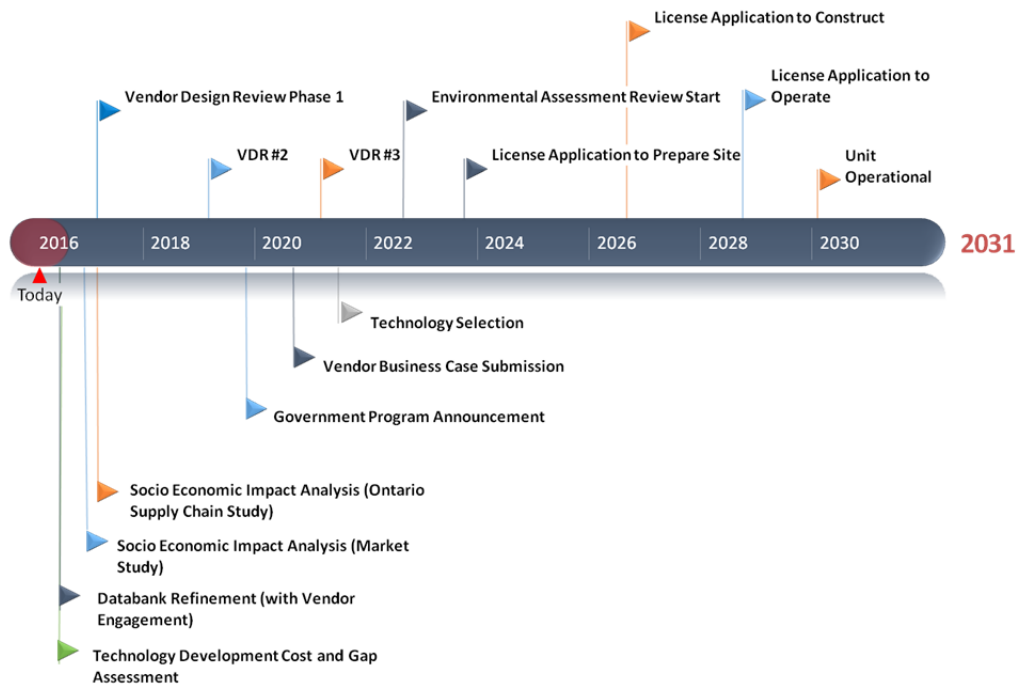
Deployment Timeline and Next Steps

The timeline for the deployment of SMRs in Ontario is produced based on the latest industry development state. In the reference case depicted below, the first site-specific license application could be submitted by an industry front runner around 2022-2023, with potential first-unit operation in 2030. This study recommends that several follow-up studies and government actions be taken (described in detail in Section 9.5). The potential timelines for these actions to be taken to maximize Ontario's influence in the industry are also indicated. Note that the flags above the timeline below indicate potential vendor activities, while those below identify recommended government actions.

Prior to announcement of a potential program, necessary key government actions may include engagement with the Ministry of Northern Development and Mines and the nuclear operators in Ontario in regards to potential SMR deployment. An additional necessary action may include wider discussion with the federal government, its agencies, and nuclear industry partners regarding the following issues and policy implications:

1. A potential pilot project site;
2. Qualified Operator;
3. A business model (e.g., P3);
4. Economic development;
5. Nuclear innovation and research at universities, supply chain development; and
6. The level of government support required.

Ontario Ministry of Energy - SMR Deployment Feasibility Study
 Feasibility of the Potential Deployment of Small Modular Reactors (SMRs) in Ontario - June 2, 2016



1. Introduction

In order for the province to properly assess the benefits and risks associated with deployment of Small Modular Reactors (SMRs), Hatch has produced this feasibility study report for the Ministry of Energy Ontario to examine the deployment feasibility of small modular reactors (SMRs) in northern Ontario as a means of providing power to remote mines. The purpose of the study is to have the SMR designs evaluated against pre-determined criteria for off-grid, remote mining application, such as in the Ring of Fire, as an example. The pre-determined criteria include, but are not limited to, the important consideration of the environmental impact, economics, licensability in Canada, availability of funding to advance deployment, and the time required to achieve commercial operation.

In addition, Natural Resources Canada (NRCan) is participating in the study to examine the feasibility of SMR deployment in remote communities and remote mines in northern Canada.

The study first establishes the SMR deployment feasibility assessment methodologies and tools. The study then uses this multi-dimensional assessment method to examine:

- The SMR industry's organizational and technological maturity as well as its readiness for deployment at remote mines in Ontario (see: Section 1.1 Background, Section 7.2 Design Specific Data, Section 7.4 Generic Data (Nuclear)).
- The proposed SMR designs which are better poised to meet the site characteristics and user requirements in northern Ontario (see: Section 7.1.3 Small Modular Reactor Shortlist, Section 8.1 Technology Suitability Evaluation, Section 8.2 Technology Deployment Potential Evaluation).
- The key parameters which influence the economics of SMR deployment against other alternatives and the sensitivity of design and operational uncertainties on the overall financial evaluation results (see: Section 8.3 Financial).

1.1 Background

Several SMR vendors have recently established themselves in Canada and initiated dialogue with the regulator, suppliers, utilities, governments and potential customers in regards to potential SMR deployment at remote mines. The recent increase in vendor activities have been noticed by Canadian stakeholders who are now observing the industry developments closely.

These vendors can be generally grouped into two categories; vendors who are developing utility-scale SMRs for main grid applications and vendors who are developing very small SMRs, sometimes called micro-SMRs or vSMRs, for niche market applications such as remote mines.

The former group includes companies with sizable corporate coffers and advanced R&D programs, such as mPower, NuScale and Westinghouse. This group of vendors are mostly

developing integral pressurized water reactors (IPWRs) with hundreds of megawatt output capacity. The latter group, with some exceptions, mostly consists of recently established and generally underfunded venture companies with preliminary technology concepts and initial business strategies. This group is aiming to develop micro-sized reactors that can produce a few megawatts (MW) to a few tens of megawatts with the hope of replacing diesel power plants in remote locations where energy costs are very high. The focus of this report is on the technologies proposed by the micro-SMR developers for remote mining applications.

In general, the rationale for applications of SMRs in remote areas seems to resonate well with many stakeholders. The challenges with diesel power generation at remote mines are well known; the power costs are high; fuel transportation logistics are challenging; and there are environmental concerns with diesel spills and greenhouse gas (GHG) emissions. Small nuclear reactors can potentially resolve these challenges. The fuel has a very high energy density which can potentially simplify the fuel transportation logistics. While small nuclear reactors cannot produce electricity at a rate as that from large central nuclear station (e.g. 1000 MWe) due to the absence of economies of scale, they are potentially more economical than diesel power plants. In addition, nuclear power is a low GHG-emitting electricity source.

The proponents of SMRs emphasize these benefits of SMR use at remote mines, although a verification of the claims as well as a deployment feasibility evaluation, including financial, technology and vendor-readiness assessments, are yet to be performed by a neutral third party. Several countries, including the United States, the United Kingdom, South Korea (in Saudi Arabia) and China, are actively investigating the feasibility of SMR deployment in their countries. However, their studies are all based on utility-scale IPWRs which are not readily transferable to the remote application of micro-SMRs. Thus, this study aims to address this knowledge gap in the current understanding of micro-SMR deployment at remote mines, specifically in northern Ontario.

1.2 Historical SMRs in Remote Applications

Before nuclear power plant sizes started to grow significantly over the last few decades in order to achieve economies of scale, they were all initially small (i.e., Canadian Nuclear Power Demonstration had a 19.5 MWe power output and US Shipping Port Atomic Power Station had a 60 MWe power output).

The use of small nuclear power plants to power communities and industrial operations in remote areas is not a new idea. The US military operated a few small nuclear power plants (NPPs) to power their bases in extremely remote locations². On the civilian side, there is an operating power plant in Bilibino, Russia³, that provides 48 MWe (peak) of electricity and heat to a nearby gold mine, greenhouse and town. In the United States, the town of Galina, Alaska, examined the possibility of deploying Toshiba 4S technology to replace the diesel power generating capacity in 2004. The 10-megawatt reactor would have been buried

² https://en.wikipedia.org/wiki/Army_Nuclear_Power_Program, accessed on December 23, 2015.

³ <http://bilnpp.rosenergoatom.ru/eng/>, last accessed on December 23, 2015.

underground and fuel would have lasted for 30 years. But the project never began due to the cost and uncertainties associated with the mandatory and lengthy process of gaining approval by the Nuclear Regulatory Commission⁴. In 2007, a US-based company called Hyperion (now known as Gen4Energy Inc.) was established to develop a 25 MWe lead bismuth cooled fast reactor.

In Canada, Atomic Energy of Canada Limited (AECL) developed a few reactors to power military installations in the Arctic and remote communities in northern Canada, including Slowpoke Energy System 10⁵ and Compact Nuclear Power Source⁶.

Several technologies, including the heat pipe system and organic Rankine cycle generators, were developed. In 2009, the Canadian Remote Power Corporation was formed as a subsidiary of Western Troy Capital Resources Inc., a junior mining company located in Toronto, to identify a small nuclear reactor technology for the purposes of providing power to support its remote mining operations in Canada⁷. This is probably the first Canadian example of a private sector company trying to become a nuclear power provider for remote locations. The company appears to now be dissolved and the exact cause of the failure is not known. Since then, several venture companies have been established in Canada with exactly the same business goals. Some of these companies are analyzed in this report.

⁴ Newsminer, http://www.newsminer.com/news/local_news/why-nuclear-energy-is-on-hold-for-alaska/article_51958987-2a69-5528-aa4b-fd2755913460.html, last accessed on February 12, 2016.

⁵ Ian J. Slater, Atomic Energy Canada Limited and Next-generation Nuclear Reactors, Journal of the International Committee for the History of Technology, Volume 11, 2005.

⁶ <http://www.computare.org/Support%20documents/Guests/Computare%202012%20PDF%20WFS/Presentations/Reactors/3-Ken%20Kozier%20Presentation.pdf>, last accessed on December 23, 2015.

⁷ <http://www.marketwired.com/press-release/western-troy-completes-drilling-schefferville-gold-prospect-forms-canadian-remote-power-tsx-venture-wry-1068389.htm>, last accessed December 23, 2015.

2. Methodology

While the concept of deploying very small modular reactors in remote mines has existed for years, a methodology to evaluate their deployment feasibility has not been well established. Such an evaluation is further complicated by the fact that many of the proposed SMRs only exist in design concepts and the Canadian regulatory licensing process has not been applied to any of these designs yet. With almost a total absence of reliable benchmarking data, some of the critical questions that the Canadian SMR stakeholders are asking today are listed below:

- Are SMRs licensable and what are SMR licensing costs?
- Is there an economic case for SMRs?
- What is the first-of-a-kind and nth-unit SMR capital cost if factory-based manufacturing can be assumed? What are the applicable scaling factors for economies of scale and learning effects?
- Can a fuelled reactor be transported to an operating site?
- Can SMRs operate with minimum or no staffing complements?
- What is the security requirement?
- What is the licensing process time?

There are many other issues in addition to the above questions for which the SMR stakeholders are trying to obtain definitive answers while the vendors establish business cases and secure adequate development funding. The Class I nuclear facility licensing process in Canada is technology, site and licensee-specific. Unfortunately, these critical issues that need to be considered in the planning period will not be settled until an SMR vendor or their operator actually reaches the licensing application and n-th unit construction stages. In the absence of a precedent-setting example in Canada, it appears that the vendors are relying on crude information and potentially unvalidated assumptions on which to currently base their SMR business cases.

In summary, the information necessary to evaluate the deployment feasibility of SMRs currently is in a state of flux and subject to a large degree of ambiguity by its very nature. Such information includes the technologies' design, safety characteristics, ease of fabrication, capital cost, lifetime economics, applicability of current regulatory processes and expected outcomes, estimated effort to go through licensing and on-site security operator requirements.

As a result, rather than trying to assign definitive but unverifiable answers to those questions, this study attempts to answer the question of SMR deployment feasibility in northern Ontario mines by establishing what the functional and economic parameters might be for SMRs to be competitive against incumbent technologies. The key methodology in this study is to establish the target conditions at which SMR deployment becomes feasible and to examine the current technical, regulatory and economic parameters for a few select SMRs in order to estimate the margin between the deployability conditions and the current SMR development progress.

More specifically, this study will examine the following four areas:

- Technology compatibility: how well do the proposed SMR technologies meet customers' needs?
- Technology readiness: how ready are SMR technologies for commercial deployment?
- Vendor readiness: how credible are the vendors as nuclear technology developers?
- Economic competitiveness: what is the relative competitiveness against the incumbent technology (e.g. diesel generators)? What are the critical cost parameters and the threshold values at which the economic competitiveness exists or fails?

2.1 Methodology Overview

Hatch adapted its multi-dimensional energy technology evaluation methodology around the scope and requirements of this study. The resultant methodology is shown in Figure 2-1.

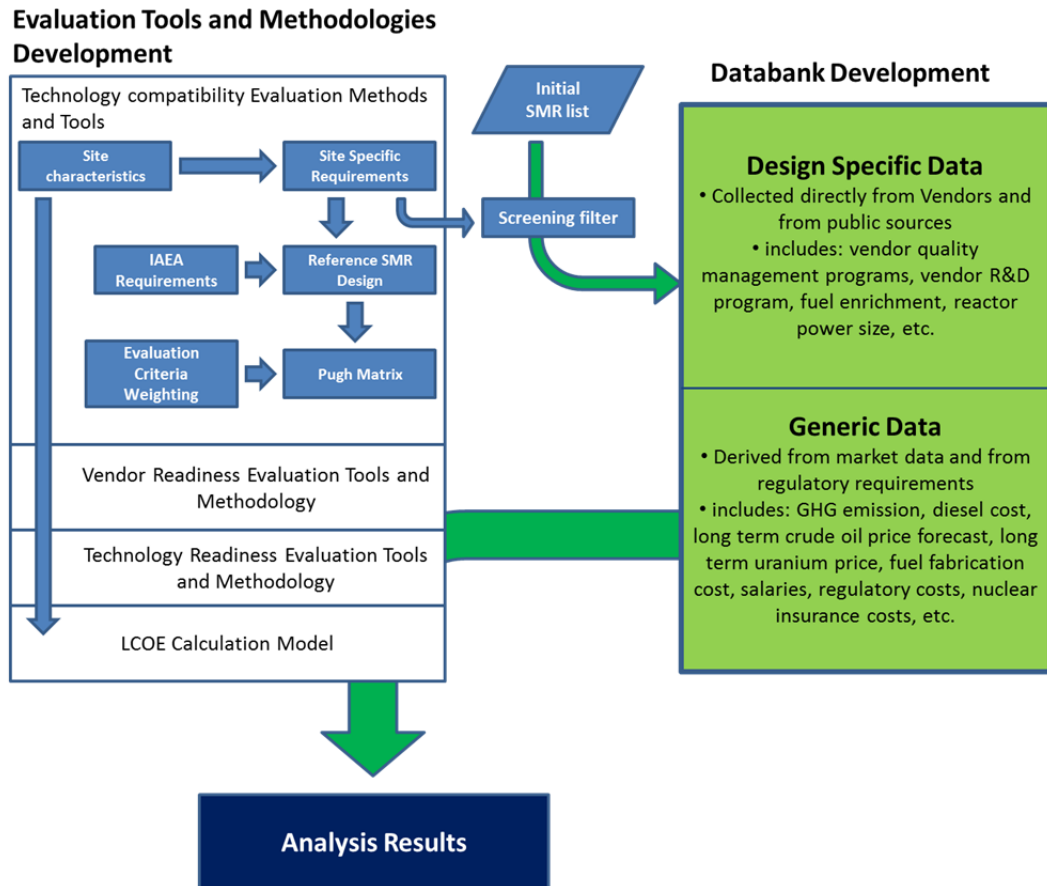


Figure 2-1: Hatch Multi-dimensional Energy Project Evaluation Methodology modified for Ontario SMR Deployment Feasibility Analysis

To enable the investigation, Hatch has modified in-house evaluation methodologies and associated tools, and established a databank that contains an initial set of technology neutral and design specific data that can be loaded to the analysis tools. It is intended that these tools are further refined and the databank updated when a significant development in the SMR industry occurs or when the Ministry of Energy wishes to re-examine the industry development again in the future. While Hatch anticipates that its tools and methodology will hold for future evaluations, the databank will require significant updates as the SMR industry progresses along the road to deployment.

2.2 SMR Evaluation Tool Development

2.2.1 *Technology Compatibility Assessment*

Hatch methodology for technology compatibility assessment, based on a Pugh matrix, is tailored to assess the technology compatibility of an SMR with remote northern Ontario location requirements. The characteristics of remote mines in northern Ontario are examined to establish the site conditions and to develop the site-specific user requirements. These requirements are further combined with applicable IAEA user considerations⁸ to develop the technology requirements and the reference SMR design features for northern Ontario applications in turn. The technology requirements are also processed to create the initial screening filter which was later used on a comprehensive SMR list to identify the designs that would be further analyzed.

In addition to the reference SMR design features, criteria weighting is necessary for a Pugh matrix evaluation. The weighting scale was developed by assigning importance scores to each evaluation criteria and their categories, and then normalizing the scores. This process eliminated the evaluation bias that comes from having a different number of evaluation criteria under each category, such as economics, safety, security, etc. The importance scores were independently provided by several stakeholders in this study, including the Ontario Ministry of Energy, the Ministry of Northern Development and Mines, Natural Resources Canada and Hatch. The statistical distribution of the scores was examined to verify whether consensus agreements were reached on the scaling factors.

2.2.2 *Vendor Readiness Assessment*

The Vendor Readiness Level Evaluation Tools and Methodology were previously developed by Hatch through an adaption of NASA's technology readiness level (TRL) assessment methodology⁹, and customized to address the SMR industry. In addition, Hatch has identified the critical vendor elements for readiness evaluation. The assessment is designed to indicate the gap between a theoretical vendor who could successfully deploy an SMR technology in Canada and the SMR vendors under evaluation in this study.

2.2.3 *Technology Readiness Assessment*

The Technology Readiness Level Evaluation Tools and Methodology were adapted from the U.S. DOE's TRL methodology¹⁰, which itself was an adaption of NASA's TRL methodology with modification for nuclear technology evaluation. Further, Hatch identified critical technology elements applicable for the evaluation. The assessment is designed to indicate the gap between a mature SMR technology and the analyzed SMR designs.

⁸ *Common User Considerations (CUC) by Developing Countries for Future Nuclear Energy Systems: Report of Stage*

1

⁹ Technology Readiness Level, http://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf, last accessed January 24, 2016.

¹⁰ Technology Readiness Assessment Guide, U.S Department of Energy, DOE G-413.3-4A, Washington, D.C., 2011.

2.2.4 *LCOE Calculation*

Hatch energy project economics evaluation model was modified for this study to calculate the Levelized Cost of Electricity (see: Section 6.4 for explanation for LCOE) of proposed SMRs based on initial input values and identify the target LCOE under which SMRs become economically competitive to incumbent technologies (see: Section 8.3.1). The resultant variation of the model is specifically tuned to assess SMR economics in a northern Ontario application based on the characteristics of remote mines.

2.3 *SMR Evaluation Databank Development*

Another major effort in this study was the collection and development of initial values used in various analyses, including SMR design specific data and generic nuclear and non-nuclear data.

2.3.1 *SMR Design Selection*

The study initially created a list of reactors that are classified as SMRs. This initial list was put together indiscriminately regardless of their technology types, vendor credibility, or design accuracy. The purpose of the list was to serve as a feedstock to be filtered through the screening filters and produce a short-list of SMR designs for further analysis. The names and the preliminary design information of SMR technologies are collected from public sources and from Hatch's business intelligence activities. The various public sources utilized include media publications, websites, internet forums, and other established nuclear information sources including:

- International Atomic Energy Agency (IAEA)¹¹
- The Nuclear Energy Agency (OECD/NEA)¹²
- US Department of Energy SMR Technology Resources Center¹³
- UxC Consulting Company SMR Database¹⁴

Once the screening filters are created based on site specific requirements, the initial SMR list is screened to identify the SMR designs that can potentially satisfy the deployment conditions in northern Ontario remote mines.

2.3.2 *Design Specific Data*

The technical and financial information of the SMR technologies available in the public domain are generally found to be inadequate for accurate analysis, as most of the micro-SMR designs considered in this study are still only in conceptual development. In addition to collecting design information from public sources, a questionnaire has been developed and sent to the selected technology vendors to collect supplemental information.

¹¹ Small and Medium Sized Reactors (SMRs) Development, Assessment and Deployment, <https://www.iaea.org/NuclearPower/SMR/>, last accessed December 29, 2015.

¹² The Nuclear Energy Agency, <http://www.oecd-nea.org/>, last accessed December 29, 2015.

¹³ The SMR Technology Resources Center, <https://smr.inl.gov/>, last accessed December 29, 2015.

¹⁴ UxC SMR Research Center, <http://www.uxc.com/smr/>, last accessed December 29, 2015.

The questions in the survey are designed to create the inputs for the various evaluation tools developed earlier. The questionnaire was provided to the Ministry of Energy as well as NRCAN for their inputs in advance of distribution amongst the vendors.

2.3.3 Generic Nuclear Data

The databank includes non-design specific nuclear information that is required for the analysis. This information is gathered from public sources as well as from private communication with stakeholders from the Canadian nuclear industry and previous Hatch studies. The information developed in this category includes:

- Various regulations.
- Staffing requirements estimates, including operator and security.
- Long-term uranium oxide concentrations, conversion, enrichment and fuel fabrication prices.
- Nuclear waste management cost and decommissioning cost estimates.
- High-level CAPEX estimates for SMRs (used in case a vendor does not supply sufficient data via questionnaire).
- Licensing cost estimates.

2.3.4 Generic Non-Nuclear Data

The databank also includes non-nuclear information that is necessary for the analysis. This information is gathered from public sources as well as from Hatch in-house expertise and studies. The information developed in this category includes:

- Estimates of the carbon emission cost in Ontario.
- Long-term crude oil price forecasts.
- Delivered diesel price at remote mines in Ontario.
- Lifecycle cost and operation data related to diesel reciprocating engines, including refurbishment frequency and taxes in fuel.
- Redundancy and backup power requirements in remote areas.
- Load growth forecast in Ontario remote mines.
- Long-term CAD/USD exchange rate.

2.4 Major Assumptions and Exclusions

Due to technology variation and different deployment timelines proposed by the SMR vendors, it has been decided that the vendor-side analysis, including their R&D costs and investment return requirements, will be excluded from this study to produce technology-neutral results. The implications of such a decision are as follows:

- The economic analysis will be performed based on a nth-of-a-kind (NOAK) reactor deployment instead of a first-of-a-kind reactor (FOAK) deployment.
- The effort necessary to bring a technology to a licensable status is only evaluated qualitatively.

The vendor financial considerations such as the technology development and corporate setup costs and private investors' return requirements are excluded. Ultimately, the vendors or their investors will aim to recover the initial development costs by adding profit margin to unit sales or surcharges to LCOE electricity prices. This study does not consider such cost recovery mechanisms, including the minimum number of reactors that need to be deployed to make the investment in the technology development worthwhile.

3. Deployment Site Characteristics and Descriptions

The feasibility of deployment of micro-SMRs is assessed for remote mines in northern Ontario. A summary is as follows:

- Power requirement is approximately 10-20 MWe or less per remote mine
- Ring of fire mines have been considered for transmission line connection in conjunction with nearby remote communities.
- Current power demand has been examined and forecasted based on a broad set of existing similar sample mines
- Current diesel engine configuration is N+2. Typical diesel capacity is 180% of peak demand.
- Typical mine lifetime of approximately 15-25 years with constant load profile and no growth. Load following capability not necessary or practical.

3.1 General Description of Northern Ontario

The areas of interest for this study are situated in the northernmost parts of Ontario, isolated from any major cities. The climate in these areas is classified as subarctic. The winters are long and cold while the summers are cool to warm, as evident in the climate chart for Big Trout Lake shown in Figure 3-1. Due to the long winters and relatively cool summers, the snow remains much longer than in areas further south, typically being present between October and May.

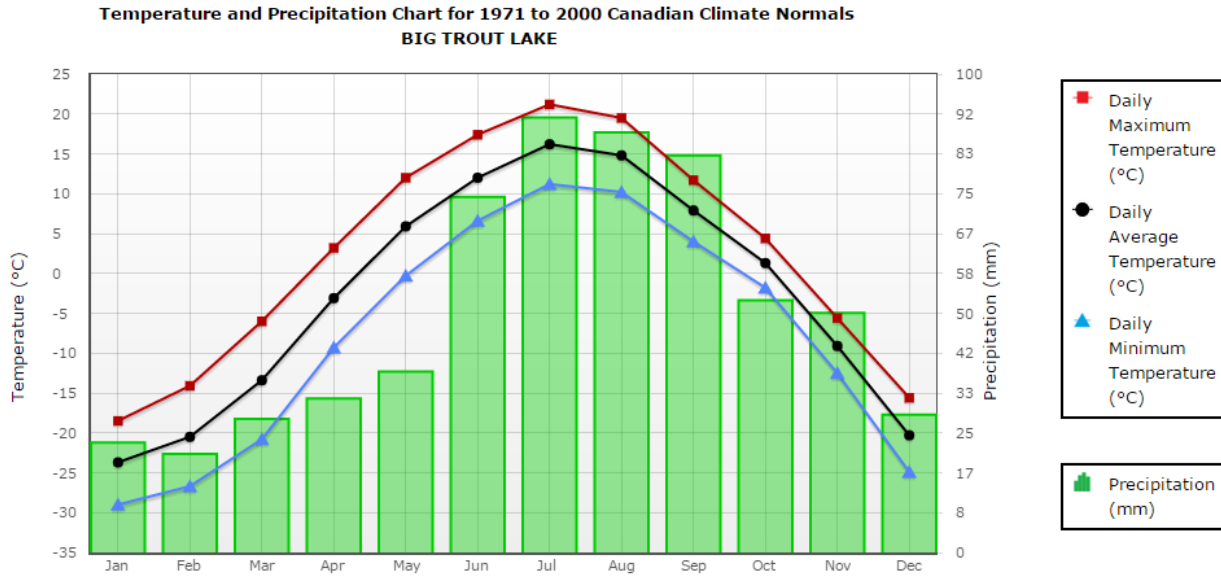


Figure 3-1: Big Trout Lake Climate Chart

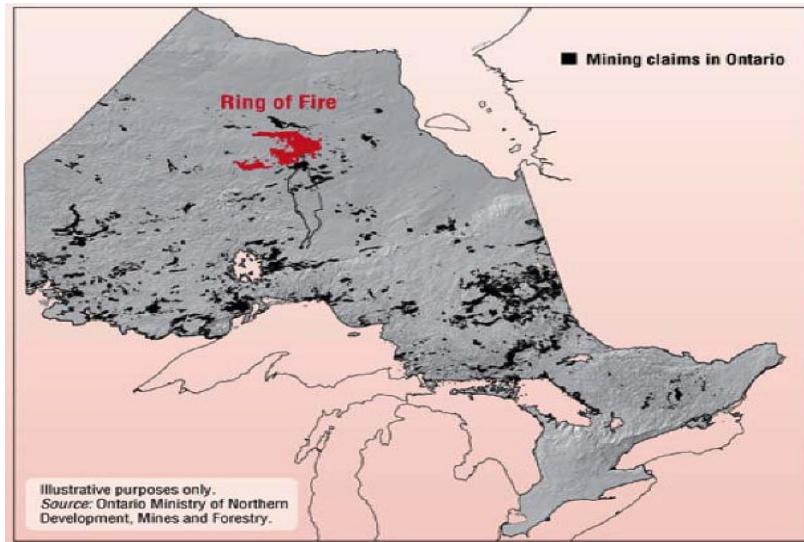


Figure 3-2 - Ring of Fire

The Ring of Fire (ROF), under consideration for remote mining deployment, is situated in the mineral-rich James Bay Lowlands. With sizeable chromite reserves, the ROF is centred on McFaulds Lake, approximately 400 km northeast of Thunder Bay.

The Hudson Bay Lowlands are distinguished by bogs and fens, slow growing forest, and tundra, forming one of the largest wetlands in the world covering an area of approximately 26 million hectares. Over two-thirds of the area is covered with trees and open muskeg, containing thousands of small lakes and bodies of water. The lowlands provide habitat for a variety of animals such as caribou, polar bears, arctic foxes, and Canada geese.

The Boreal Forest region is the largest forest region in Ontario with an area of 50 million hectares. The region contains primarily coniferous and mixed-wood forests, which varies depending on soil, climate, topography, and other factors.

3.2 Description of Off-grid Remote Mines in Northern Ontario

In the investigation of SMR applications for northern Ontario mines, emphasis has been placed on the Ring of Fire (ROF) region. There are currently no operating mines in this region.

3.2.1 Current Status of the Ring of Fire

The ROF has been under investigation since the early 2000s, when significant deposits of copper, zinc, nickel, platinum, vanadium, and gold were found. Setting precedence for North America, large quantities of chromite were also found in the region. As a result of this, the region is considered an extraordinary economic opportunity. The Ontario Chamber of Commerce has estimated that in the first 10 years of its development, the ROF will generate up to \$9.4 billion in Gross Domestic Product¹⁵. Despite this, no mines have been developed as of yet due to a significant infrastructure gap in the region, a short supply of skilled labour, ongoing negotiations with Aboriginal communities, and the need for cutting-edge technologies to minimize environmental impacts.

3.2.2 Prospective Mine Sites

3.2.2.1 Eagle's Nest

Noront Resource's Eagle's Nest Mine is widely believed to be the pilot project for the Ring of Fire region. Currently in its permitting phase, Eagle's Nest is a high-grade nickel-copper-platinum group element deposit that is expected to produce around 3,000 tonnes of ore per day for an anticipated mine life of 11 years with the potential for 9 additional years¹⁶. A complete table of measured, indicated, and inferred resources at Eagle's Nest can be found in Table 3-1.

Table 3-1: Eagle's Nest Reserves and Resources

Mineral Reserves and Resources					
Category	Tonnes (000)	Nickel (%)	Copper (%)	Platinum (gpt)	Paladium (gpt)
Proven and Probable	11,131	1.68	0.87	0.89	3.09

¹⁵ Beneath the Surface: Uncovering the Economic Potential of Ontario's Ring of Fire. Ontario Chamber of Commerce, 2014.

¹⁶ Noront Resources, Eagle's Nest Mine, <http://norontresources.com/projects/eagles-nest-mine/>

Mineral Reserves and Resources					
Reserves					
Inferred Resources	8,966	1.10	1.14	1.16	3.49

Noront received its Approved Terms of Reference for the Eagle's Nest Environmental Assessment (EA) from the Ministry of Environment and Climate Change in June 2015, and since then they have been working on a series of amendments to the EA in order to gain project approval. Current projections indicate that the project, which will include a mine site, transportation corridor, and trans-load facility, will have a 16-year life encompassing construction (3 years), operation (at least 11 years), closure (2 years) and post-closure (at least 5 years). The mine is expected to reach production in 2018.

3.2.2.2 *Black Thor and Black Label*

Noront Resources purchased all assets, properties and interests from Cliffs Natural Resources in April 2015, acquiring interests in 9 mining claims including Black Thor and Black Label chromite deposits. A 2013 feasibility analysis by Cliffs Natural Resources contemplated an open-pit mine for Black Thor producing a diluted grade of 30.7% Cr₂O₃ ore over a 30-year mine life¹⁷. A more recent Technical Report by Noront Resources estimates 137.7 million tonnes grading 31.5% Cr₂O₃ of measured and indicated resources for Black Thor and 5.4 million tonnes grading 25.3% Cr₂O₃ of indicated resources for Black Label. A more detailed summary of the estimates is provided in Table 3-2.

Table 3-2: Black Thor and Black Label Resources¹⁸

Classification	Tonnes (millions)	% Cr ₂ O ₃
Black Thor		
Measured Resources	107.6	32.2
Indicated Resources	30.2	28.9
Meas. & Ind. Resources	137.7	31.5
Inferred Resources	26.8	29.3
Black Label		
Measured Resources	-	-
Indicated Resources	5.4	25.3
Meas. & Ind. Resources	5.4	25.3
Inferred Resources	0.9	22.8

It is widely accepted that Black Thor is the next project in the pipeline in the ROF following the results of Eagle's Nest.

3.2.2.3 *Additional Sites*

While there are over 12,000 claim units staked in the ROF as of 2013, the two largest and most progressed projects are Eagle's Nest and Black Thor. In estimating the economic

¹⁷ Noront Resources, Black Thor & Black Label Deposits, <http://norontresources.com/projects/black-thor-black-label-deposits/>

¹⁸ Technical Report – Black Thor, Black Label and Big Daddy Chromite Deposits, Sibley Basin Group, Prepared for Noront Resources Ltd., 2015

potential of the ROF, the Ontario Chamber of Commerce (OCC) used these two mines to build their conservative scenario analysis. To build their optimistic scenario, the OCC accounts for three additional projects that were believed to be next in line. These were Probe Mine's Black Creek Chromite project, Noront Resource's (70%) and Canada Chrome Mining Corporation's (30%) Big Daddy Deposit, and Noront Resource's (85%) and KWG Resource's (15%) McFaulds project. Noront Resource's also views the Blackbird Deposit as being in their pipeline following Eagle's Nest and Black Thor. While there are many more potential sites in the Ring of Fire, none are anticipated to begin commercial production before at least 2020.

3.2.3 **Current Power Situation**

Remote mines in Ontario are primarily powered by diesel generators when no connection to the grid is available. Diesel is transported to the mines via water or land depending on the mine site location.

Generating facilities developed to serve remote mining operations are typically configured with multiple diesel gensets sized to be capable of delivering the peak power demand with sufficient spinning reserve and spare generating units to avoid a blackout in event of a forced outage. Plants are frequently configured based on an "N+2" philosophy, where "N" is the number of diesel generating units required to meet the peak demand at between 80 to 85% of their rated generating capacity. A six unit generating facility is common (N=4), where four gensets are operating, one is on hot standby (spinning reserve), and one is assumed to be undergoing maintenance at any given time.

Expanding the above definition, we can take "N" to be the number of SMR units required to meet the peak demand at between 80 to 85% of their rate generating capacity, and "M" to be the diesel backup with a capacity of 1 SMR. A remote mine utilizing SMR technology would then likely adopt the configuration "N+M+1", where N nuclear units would be operating while additional backup capacity is provided by reciprocating engine gensets.

3.2.4 **Load characteristics**

Mines typically experience a constant load operating continuously with occasional sudden load or frequency fluctuations due to mining or hoisting equipment trips and restarts.

Typical mine load demand is between 15-50 MWe. For remote mines under consideration for development in the Ring of Fire, load demand is expected to be between 20-30 MWe. According to a 2012 report by Micon International Limited¹⁹, power for the potential future mine at the Eagle's Nest site will be provided by a dedicated eight diesel generator power plant design with an N+2 configuration and a continuous output of 21.3 MW. A summary of the estimated power loads for Eagle's Nest can be found in Table 3-3.

¹⁹ NI 43-101 Technical Report, Feasibility Study, McFaulds Lake Property, Eagle's Nest Project, James Bay Lowlands, Ontario, Canada, October 19, 2012

Table 3-3: Eagle's Nest Electrical Power Load Summary

Area	Peak Load		Average Load	
	MW	MVA	MW	MVA
Process plant	14.74	17.33	11.08	13.06
Site surface infrastructure	1.95	2.30	1.96	2.30
Ramp and mine	5.35	6.29	4.55	5.35
Total	22.05	25.93	17.59	20.71

The presented reference long-term forecast to 2033 for the Ring of Fire subsystem is shown in

Table 3-4. The low forecast demand assumes no mining development, with the 7 MW allocated strictly to the remote communities. The reference case likely corresponds to the planned development of the Eagle's Nest mine, widely considered to be the pilot project for the Ring of Fire. The high forecast demand assumes more-than-expected mining development, either through additional mines or Eagle's Nest expansion.

Table 3-4: Long-term Load Forecast for Ring of Fire Subsystem

Low	Reference	High
7 MW	29 MW	73 MW

3.2.5 Generic Canadian Remote Mine Description

3.2.5.1 Economics of Grid-Connected vs. Genset-Connected Mines

Due to the low number of inhabitants in the region, a majority of the future electrical demand growth around the ROF will be driven by the mining industry. Due to the high operating costs associated with mining in such a remote location, only high-value ores are economical for extraction. The grade of ore, as well as the energy and cost required to extract it, will dictate the extent of mine development and subsequently the electrical demand growth in the area. The volatility of this commodity-based industry, where the value of ores is not static, results in a great deal of uncertainty when attempting to predict future energy demands. Thus, it is important to consider various electrical demand growth scenarios. Establishing base or reference case scenarios involves investigations into predicted demands at planned mines in the ROF, as well as a comparison with the demands of similar remote mines under comparable ambient conditions.

In order to develop a list of existing mines that can justifiably be used in a comparison with mines proposed for the ROF site, it is necessary to only select remote mines that are powered solely by diesel or natural gas generators ("gensets"). The reason for this is that grid connected mines can operate with much lower grade ore due to their significantly lower operating costs.

Conversely, genset-powered mines have much higher operating costs arising primarily from the transportation of fuel to site and the transportation of raw material for processing from site (the economics often don't justify constructing on-site mills at such mines). Since the only two

ROF sites that have advanced into further developmental stages (i.e., Black Thor and Eagle's Nest) will only be mined for ore with the highest value, the energy demand of these proposed mines must be compared to existing genset-powered mines that are only economical due to their high-grade ore.

3.2.5.2 *Existing Northern Canadian Mines*

For remote mining site characteristic development, Hatch used the data from comparable northern Ontario and other Canadian remote mines. There are limited operating facilities in northern Ontario that are supplied by gensets. This data has been included; however it has also been supplemented with additional data from northern remote mines outside of Ontario to obtain a larger sample size and therefore greater accuracy. Existing remote genset-powered mines in locations such as Africa or Australia also operate under hostile conditions; their data has been excluded from this comparison because their ambient conditions are not comparable to those in Northern Ontario.

Based on prior Hatch experience, the listed mines in Table 3-5 are comparable to the proposed Eagle's Nest and Black Thor deposits in the ROF. An observation of this table indicates that most genset-powered mines in northern regions employ an installed capacity of 20 – 60 MW to service peak demands between 10 – 40 MW. A couple of mines operate under lesser demands, while only one operates under a significantly higher demand.

Table 3-5: Remote Genset-Powered Northern Mines

Site Name/Description	Location	Commodity	Status	Type	Fuel	Installed Generation (MW)	Installed Generation Breakdown (qty x MW)	Peak Demand, Measured or Estimated (MW)	Thermal Demand (MWth)	Redundancy
Nickel Mine	Newfoundland	Nickel	Operating	Gensets	Diesel	25	6 x 4.125	12	Yes	N+2
Gold Mine	Nunavut	Gold	Operating	Gensets	Diesel	26	6 x 4.4	22	7.9	N+1
Iron Ore Port	Nunavut	Iron Ore	Operating	Gensets	Diesel	9.52	7 x 1.7 MVA	6.8	0	
Iron Ore Mine	Nunavut	Iron Ore	Operating	Gensets	Diesel	8.16	6 x 1.7 MVA	5.4	0	
Iron Ore Port/Mine Expansion	Nunavut	Iron Ore	Evaluation	Gensets	Diesel	39		28		
Zinc Mine	Nunavut	Zinc	Past Study	Gensets	Diesel	60	6 x 10	40	20	N+2
Gold Mine	Nunavut	Gold	Past Study	Gensets	Diesel	34	5 x 6.89	28	22	N+1
Diamond Mine	NWT	Diamond	Operating	Gensets	Diesel	29.2	6x3.6 + 3x1.825 + 2x1.1	22.1		
Chromite Mine and Concentrator	N. Ontario	Chromite	Past Study	Gensets	CNG / Diesel	26	5 x 5.2	13.7	19	
Nickel Mine and Concentrator	N. Quebec	Ni/Cu/Co	Operating	Gensets	Diesel			25		
Nickel Mine and Concentrator	N. Quebec	Ni/Cu/Co	Operating	Gensets	Diesel	33.5	6x3.6 + 4.3 + 3x1.8 + 2x1.1	15.5	14.2	N+2

3.2.6 *Special Conditions*

3.2.6.1 *Lifespan of a Canadian Mine*

The typical operating lifespan of a Canadian mine is usually between 10-20 years. The complete lifespan however, encompassing the pre- and post-production phases, can be much longer. According to the Ontario Mining Association²⁰, the life of mine can generally be outlined as follows:

- Prospecting & Claim Staking: 1-2 years.
- Basic & Intermediate Exploration: 3-4 years.
- Advanced Exploration 5-10 years.
- Development & Production 20 years.
- Closure & Rehabilitation 2-10 years.
- Monitoring 5-100 years.

The above can loosely be grouped into five major stages, as depicted in Figure 3-3.

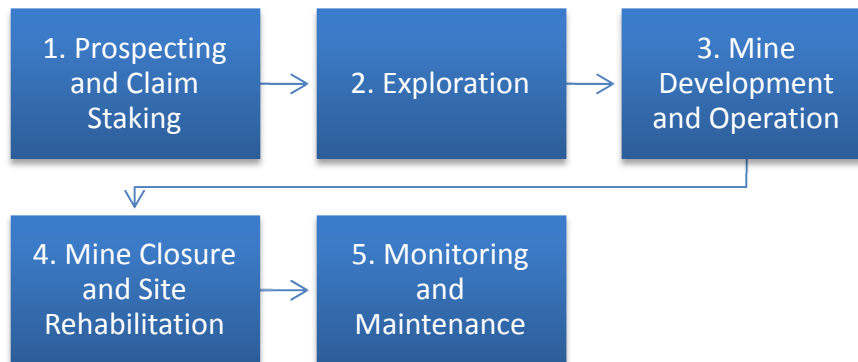


Figure 3-3: The Five Stages of Mining

As can be seen in Figure 3-4, courtesy of Ontario's Ministry of Northern Development and Mines, heavy investments are made in the mining sequence before any production commences.

²⁰ Mining 101, Ontario Mining Association, <http://www.oma.on.ca/en/ontariomining/Mining101.asp>

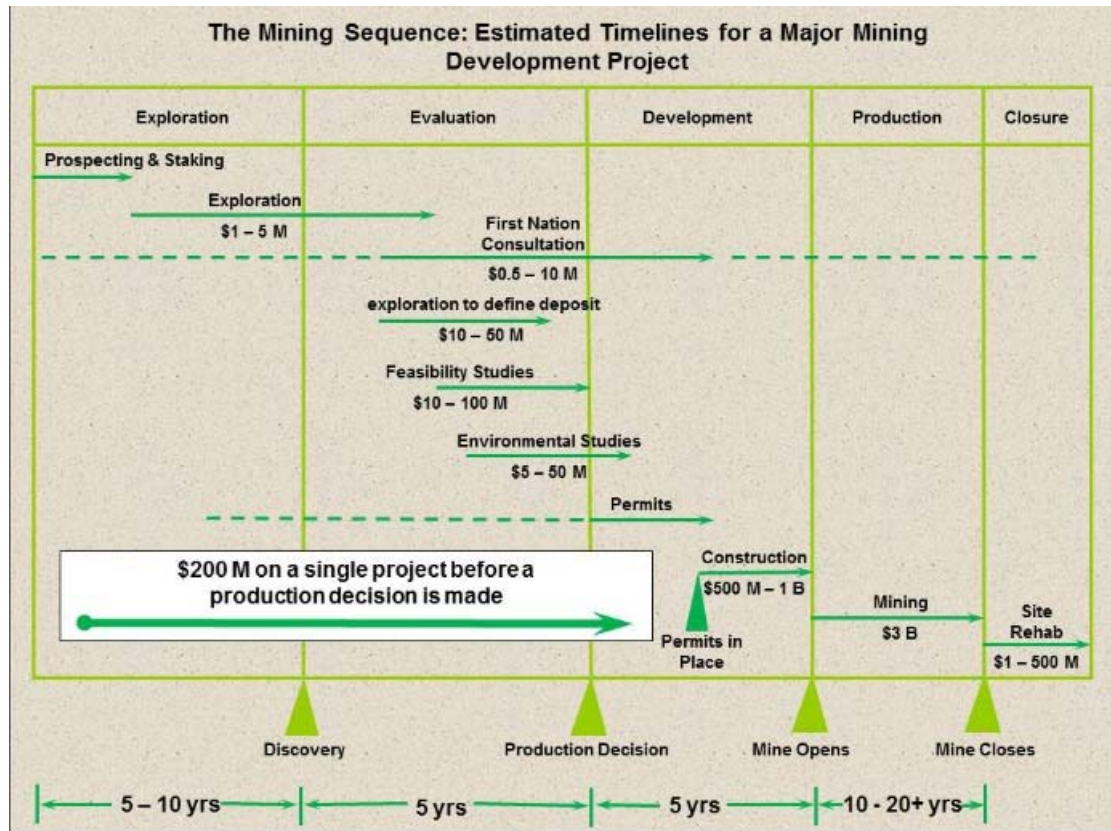


Figure 3-4: Estimated Timelines for a Major Mining Development Project

These costs are provided for illustrative purposes only, and are outside the scope of this study. This study assumes 20-year production times, and only considers the energy generation costs associated with this operation. All of the other phases of the mining sequence are assumed to be powered using temporary sources which are excluded from scope.

3.2.6.2 Seismic Concerns

3.2.6.2.1 CNSC Seismic Regulations

As per REGDOC-2.5.2, the design of new nuclear power plants in Canada must include the seismic qualification of all structures, systems, and components (SSCs) that align with Canadian national – or equivalent – standards²¹. The design authority shall ensure that seismically qualified SSCs important to safety are qualified to a design-basis earthquake (DBE). A beyond-design-basis earthquake (BDBE) shall be identified, and SSCs credited to function during and after a BDBE shall be demonstrated to be capable of performing their intended function under the expected conditions.

²¹ REGDOC-2.5.2, Design of Reactor Facilities: Nuclear Power Plants, Canadian Nuclear Safety Commission.

In addition to qualifying safety-critical SSCs for DBEs and BDBEs, reactors installed for mining applications would also have to consider less severe but more frequent seismicity associated with the mining activities.

3.2.6.2.2 Mining-Induced Seismicity

All underground mines observe some form of seismicity, phenomenon which can be damaging to energy generating equipment if not appropriately designed. These seismic events occur due to any source of rock fracture and ground movement, including blasting, fault slip, or rockbursts.

In addition to the CNSC-imposed seismic design criteria for DBEs and BDBEs described above, SMRs installed for mining applications will require additional provisions to eliminate any repercussions and maintain operability throughout the various sources of mining-induced seismicity.

3.2.6.2.3 Standardizing Seismic Designs

A DBE represents the probabilistic estimate of a site-specific earthquake with the most severe impact. DBEs used to design new nuclear facilities as per the CNSC seismic regulations vary between locations. In this sense, the requirements for seismically qualifying safety-related SSCs has traditionally varied from facility to facility.

By definition, SMRs are attempting to be plug-and-play power plants. They are aiming to be deployable in virtually all geographical locations, without the need to be modified for site-specific conditions. In order for this to be plausible, the seismic design of the SMRs will need to be standardized such that they remain seismically qualified at all locations and under a variety of DBEs and BDBEs.

4. Technology Suitability Evaluation Tool

The purpose of the technology suitability evaluation tool is to determine which SMR technology is most suitable for deployment in northern Ontario mines, independent of technology or vendor readiness. Hatch’s proprietary variation of a Pugh matrix, also known as a decision-matrix, will be used to compare SMR technologies. A Pugh matrix is a tool used to compare options by assigning rankings and importance weightings to specific criteria based on available data. Some criteria are quantitative by nature while others are qualitative and must be assigned rankings based on professional and expert judgement.

In order to compare multiple SMR technologies, a baseline “reference SMR” was developed prior to ranking. Criteria identified in the development of the reference SMR are the criteria all SMR’s shall be compared against.

4.1 Reference SMR and Criteria Development

A set of specific criteria for a hypothetical reference SMR were developed to provide a baseline for the comparative analysis. The rationale in developing a hypothetical reference reactor is to identify all important desired features relevant to SMR deployment in remote mines. From the desired features, baseline criteria can be assigned to which each considered SMR can be compared against. Hatch’s proprietary baseline development methodology used to develop the desired feature baseline criteria is shown in Figure 4-1.



Figure 4-1: Reference SMR Development Methodology

To identify and develop all important considerations and issues relating to SMR deployment in remote areas, the following was considered:

1. **Descriptions of remote mines in northern Ontario** – Based on the descriptions and characteristics described in Section 3 a number of specific issues and considerations were identified.
2. **IAEA Publication No. NP-T-2-1, Common User Considerations (CUC) by Developing Countries for Future Nuclear Energy Systems: Report of Stage 1** – This publication describes common characteristics of desired features requested by potential users of small nuclear power plants in remote locations (not specific to northern Ontario or Canada). It covers general technical and economic characteristics of desired nuclear power plants and associated services and supports.

By considering the descriptions and the CUCs, both application specific and non-application specific desired features have been developed. Quantitative and/or qualitative baseline criteria have been assigned to each desired feature in an effort to establish a baseline for the

comparison of considered SMR technologies. The list of desired features and baseline criteria are identified in Table 4-1 below, and are used for the Pugh Matrix Comparative Analysis discussed in Section 8.1. Some desired features have been identified by both sources, as has been identified accordingly. The table also shows the importance of the desired features for SMR application in remote mines as determined by the stakeholders in this study (e.g. Ministry of Energy, Natural Resources Canada, Ministry of Northern Development and Mining and Hatch).

Table 4-1: SMR Considerations, Desired Features, and Baseline Criteria

Categories	Consideration	Importance	Desired Feature	Baseline Criteria
Economics (Financing)	Capital Cost	Important	Low CAPEX \$/kW compared to large NPP	≤ \$5500/kW CAD
	EPC time		EPC time to be short	≤ 4 years
	First Concrete to Operation time		First concrete to operation time short	≤ 2 years
	Plant Footprint		Smallest physical plant footprint possible to reduce site size	≤ 1600 m ²
Economics (Lifetime)	Cost of Electricity	Very Important	LCOE to be equal or less than alternative options (or large NPP)	≤ \$0.11/kWh CAD
	Recoverable Materials and Costs		Reactor materials are reusable and redeployable at other sites	At least 50% of direct cost
	Reactor Capacity for Site		Acceptable size for site based on loading requirements	<3 MW for RC, <10 MW for RM
	Plant expected life		Appropriate for respective site	40 years for RC and 20 years for RM
Site Deployability	Transportation during construction	Important	Transportation and construction of modules without additional infrastructure need	Weight of largest module ≤100 t
	Prefabrication		Reactor module is prefabricated off-site and can be installed using local resources. Plant can be constructed using local resources.	Yes
	Site Specific Civil Considerations		Plant design is above ground	Yes
	Suitability to Northern Ontario Climate		Capability of start-up and operation in Northern Ontario climate design considered	Yes
	Decommissioning and end-of-life		Easy decommissioning of the facility	Yes
Reactor and Plant Design	Base load capability	Important	Base load power provider	at least 90% CF

Categories	Consideration	Importance	Desired Feature	Baseline Criteria
	Load and frequency fluctuations		Load following capability	Yes
	Provenness Based on Operating Practices		Technology provenness demonstrated with operating practices	Yes
	Unit Standardization		NPP is based on standardized design (i.e. no changes from nth and (n+1)th unit, reactors at different sites, does not use	Yes
	Co-generation Capability		Co-generation capability is possible	Yes
Operation	Operation Cycle	Somewhat Important	Long refueling frequency	≥ 5 years
	Refueling Methodology		Refueling time is short, simple	≤ 2 weeks
	Operator Requirements		The reactor requires no on-site or no operators.	Yes
	Simple Component Replacement		Modular component replacement	Yes
	Safety System Operation		Safety systems are simple to operate, incorporation of passive safety systems	Yes
Security	IAEA Safeguard Friendliness	Very Important	Designed to accommodate IAEA non-proliferation tools and protocols (space for monitors, accounting system, etc.)	Yes
	Security		Enhanced engineering security to reduce security staff on site	≤ 20 security staff
Safety	Safety System Proof	Very Important	All safety systems are proven with OPEX available	Yes
	External Event Safety		Designed to withstand seismic (natural and man-made), tsunami, fire, explosion, flooding, airplane crash, etc.	Yes
	Radiation Exposure Approach and Dosage		ALARA principle incorporated, Worker dose is less than 20 mSv/year, Public dose is less than 1 mSv/year	Yes
	Accident Frequencies		Severe core damage frequency	≤ 10 ⁻⁵ /year
	Shutdown Safety		Decay heat removal capability	Yes

Categories	Consideration	Importance	Desired Feature	Baseline Criteria
Environmental	Environmental impacts (radioactive, chemical)	Very Important	Release of radioactive or chemical materials to the environment under regulatory limit	Zero effluent discharge
	Environmental impacts (water)		Consumes little or no water during operation	Yes
	High Level Radioactive Waste Production		Produces less high level radioactive waste than CANDU reactors.	17.9 g/MWh
	Waste Management and Storage		Secure on-site spent fuel storage for cooling	Yes

4.2 Weighting Factors

Weighting factors were calculated based on input from Hatch, Ministry of Energy Ontario (MoE), Natural Resources Canada (NRCAN), and Ministry of Northern Development of Mines Ontario (MNDM). A weighted average of inputs from all parties was calculated, allocating greater representation to inputs given by the MoE, NRCAN, and MNDM.

4.3 Rankings

Ranking the SMRs was completed by Hatch using data from the SMR Vendor Questionnaire, public sources, and expert judgment against the criteria in Table 4-1. Rankings were assigned based on the scoring criteria presented in Table 4-2. Once rankings were completed, a count of zero-scores was tallied as a representation of uncertainty.

Table 4-2: Pugh Matrix Scoring Legend

Scoring Legend	Score
Exceeds the requirements	2
Meets the requirements	1
Not applicable / not enough information available	0
Somewhat inadequate	-1
Completely lacking	-2

Results are presented in Section 8.1.

5. Technology Deployment Potential Evaluation Tools

5.1 Technology Readiness Levels (TRL)

Originally developed by NASA in the 1980s, Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. In their definition, every technology project is independently evaluated against the parameters for each technology level and assigned a TRL rating based on the project's progress. There are nine levels in total, with TRL 1 being the lowest and TRL 9 being the highest.

This study uses a slightly modified TRL model, which was originally based on the U.S. DOE model rather than NASA's. Rather than evaluate the technologies as a whole, this model separately evaluates various technology and development process elements for each SMR technology. These elements, known as Technology Readiness Areas (TRA), are as follows:

- Safety Systems
- Reactor Physics
- Thermal Hydraulics
- Materials
- Analysis Codes and Validation
- Fuel
- Control Systems

The U.S. DOE-based TRL model adopted for this study is identified in Table 5-1.

Table 5-1: U.S. DOE TRL Model²²

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	TRL 9	Actual system operated over the full range of expected mission conditions	The technology is in its final form and operated under the full range of operating mission conditions.
System Commissioning	TRL 8	Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Supporting information includes operational procedures that are virtually complete.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step-up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
Technology Demonstration	TRL 6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely

²² U.S. Department of Energy, Technology Readiness Assessment Guide, September 15, 2011.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
			represent the actual operating environment.
Technology Development	TRL 5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
	TRL 4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Research to Prove Feasibility	TRL 3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Basic Technology Research	TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Supporting information includes published research or other references that identify the principles that underlie the technology.

5.2 Vendor Readiness Levels (VRL)

In addition to evaluating the maturity of the identified SMR technologies using the TRL model, this study into the feasibility of SMR deployment in northern Ontario remote mines will also assess the maturity of the various SMR vendors. Hatch's previously developed proprietary Vendor Readiness Levels (VRL) model, with similar functionality to the above TRL model, was tailored for SMR vendor applicability. Utilizing five levels rather than nine, whereby VRL 1 is the lowest and VRL 5 is the highest, the model evaluates the growth and maturity of the identified SMR vendors against the following corporate elements known as Vendor Readiness Areas (VRA):

- Corporate structures.
- Financial.
- Eco-system (Supply Chain: Components & EPC).
- Regulatory Approval Status (Licensing: Environmental & Nuclear).
- Technology Development Status.
- Client Engagement Status.
- Stakeholder Engagement.

The various VRL levels as they correlate to the above VRAs are described in Table 5-2.

Table 5-2: Vendor Readiness Level Descriptions

Level	Corporate Structure	Financial	Ecosystem, Supply Chain	Quality Assurance Program	Regulatory Approval Status	Technology Development Status	Client Engagement Status	Stakeholder Engagement
5	Vendor organization has defined hierarchy, functional divisions, and roles. Has experienced corporate history and evolution. Organization has a board of directors. 500+ people	Vendor has a proven history of revenue, long term financial stability and strength.	Vendor has a well established, strong supply chain pool developed, approved suppliers under QA program, university and lab support, human capital development program.	Vendor has a mature and audited QA program, successfully used in past. QA program is forced on suppliers including supplier audits.	Vendor has commercial sites licensed with years of operation.	9	Vendor has paying customer(s).	All parties aligned, concerns addressed, collaborative relationship established.
4	Vendor organization has defined hierarchy, functional divisions, and roles. Organization has a board of directors 100+ people	Vendor has revenue generation from products and services.	Vendor has bare minimum supply chain adequacy.	Vendor has an existing QA program fully developed and actively used to dictate nuclear activities and performance.	Vendor has prototype site licensed. Vendor's Environmental Assessment, Vendor Design Review, Preliminary Safety Analysis, Final Safety Analysis have been completed.	7 to 8	Vendor has committed customer(s).	Stakeholder issues are being resolved. Fundamental level support outstanding issues, in depth engagement
3	Vendor has business Functional roles and structures in place, hires employees. Organization has a board of directors. 50-100 people	Vendor has customer commitment, money being spent on development, R&D, and engineering.	Vendor has some suppliers, inconsistency across supply chain.	Vendor QA Program partially developed and partially applied to activities.	Vendor's Environmental Assessment, Preliminary Safety Analysis Report have been completed.	5 to 6	Vendor has had discussion, memorandum of understanding with customers.	Stakeholder contacts have been made, issues have been identified, discussion has been started.
2	Vendor is a corporation, technical roles are defined and a growth and staffing plan has been developed. Organization has a board of directors. 10-50 People	Vendor has seed money in the bank, venture capitalists, loans, etc. Vendor has developed a business/financial plan.	Vendor has supplier commitment, MOU's, discussions. A supply chain plan has been developed.	Vendor has a QA Program development plan in place	Vendor is currently in Vendor Design Review Process.	3 to 4	Vendor has completed market analysis and developed a client engagement plan.	Stakeholders have been identified, approaches and plan are documented.
1	Organization is a business concept. 1-10 people	Vendor has no revenue and no spending.	Vendor has nothing established.	Vendor has no defined QA program.	Vendor has had an initial discussion with CNSC or none.	1 to 2	Vendor has an informal concept of the market.	No stakeholder engagement effort

6. Financial Evaluation Tool

6.1 Method

As part of the analysis of each power generation option, the LCOE for each selected technology was calculated using a modified version of Hatch's existing in-house LCOE calculator. The calculator sums up the cash flows for the entire project life based on the technology-specific values developed in the databank and determines the equivalent cost of generated electricity (LCOE) that would result in the same net present value of the associated costs of each technology.

The calculator is highly customized to account for specific load characteristics of mines, nuclear specific considerations, and various technology deployment strategies proposed by SMR vendors. Whereas Hatch's LCOE calculator tries to compare all SMR technologies on a common analysis basis, the scenarios assumed in this calculator may favour certain SMR deployment strategies such as re-deploying the core (see: Section 9.5).

The major assumptions, special considerations, and input parameters are described below.

6.2 Financial Assumptions

The following assumptions were made in the production of the cash flow model:

- The model is pre-tax.
- 100% equity is assumed (i.e., no debt accounting was used).
- LCOE is calculated based on net present value calculations of all costs and power generation.
- Cash flows are calculated annually in nominal dollars then converted to 2016 dollars.
- All future costs are adjusted based on the Canadian Consumer Price Index²³ for inflation, except when estimating long-term crude oil price which relies on EIA projections.
- The baseline calculation is performed using a 6% nominal discount rate.
- Discount rate sensitivity analysis is performed for 0% to 10% discount rates.

The calculations presented in this report are based on the following project-specific assumptions:

- The life of the project was assumed be 20 years for remote mining sites.
- All installations are assumed to start full operation on 01-Jan-2019.

²³ Statistics Canada, Consumer Price Index, historical summary (1996 to 2015), <http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm>, last accessed on January 29, 2016.

6.3 Analysis Scenarios

The initial average peak loads are assumed based on typical mining project load requirements.

The units are decommissioned in the final year of operation. Depreciation of capital assets are not considered and the remaining value of capital assets for non-redeployable SMRs are assumed to be zero at the end of the analysis cycle. For redeployable SMRs (such as in mining projects whose life is ~20 years), the portion of the initial capital costs are treated as negative capital costs.

6.4 LCOE Formula

The levelized cost of electricity is calculated as follows:

$$LCOE = \frac{NPV(CAPEX) + NPV(OPEX)}{NPV(EP)}$$

Where CAPEX is capital expenditure, OPEX is operations and maintenance costs and EP is electricity produced in kWh or in MWh. For the expenses and electricity generation that would occur in the future, the cost and electricity productions are discounted.

6.5 Major Inputs

The following assumptions are used in this LCOE calculator model.

6.5.1 Capital expenditure

The capital costs include the following entries:

- Primary technology cost: This refers to SMR capital costs. For diesel LCOE analysis, this is diesel capital cost. The primary technology cost also includes additional units that are deployed to a remote mine site throughout the project lifetime.
- Backup technology cost: Diesel backup unit capital costs are included. The backup diesel systems are added when additional SMR capacity is added to the site.
- Construction time: SMR capital costs are assumed to be spent over a 3-year period with 40%, 40% and 20% of capital expended in Year 1, 2 and 3, respectively. Diesel generators are assumed to be constructed in 2 years with 50% of the capital expended in both years.
- Frequency control system: For the mining application of SMR, 50% of the SMR capacity is supported by energy storage systems. The cost is proportional to the installed SMR capacity for the mining site.
- SMR core swap: For SMRs that have adopted the concept of a factory fuelled and transported core, core swapping costs are added to the total capital costs.

- Diesel rehabilitation: Diesel generators have a finite lifetime after which they need to be replaced or rebuilt for medium-speed machines in remote mines, it is assumed that the engines are re-built periodically and that cost is included in the OPEX.
- Spent fuel storage: For SMR designs that use on-site refueling, spent fuel storage costs are included in the CAPEX.
- Decommissioning: Decommissioning costs are applied to all SMR technology options based on their capacity in MWe.
- Redeployment credit: If an SMR technology is designed to be redeployable, including the factory fuelled core designs, the credit is provided as a negative capital cost in the year of site decommissioning.

6.5.2 O&M Costs

- Fixed parts and plant upkeep costs are estimated to be 1% of the initial primary technology capital cost.
- For all primary and backup diesel generators, the non-fuel O&M costs are included and depend on diesel generator types and their power generation.
- Staffing costs include the annual salaries for on-site operator and security personnel and off-site corporate support staffs.
- Security training: annual off-site security response team costs are included.
- Nuclear waste management fund: The long-term disposal cost of spent fuel is treated as an annual OPEX item based on the amount of power generated with nuclear fuel.
- Carbon tax credit: for SMRs, avoided diesel consumption is converted to equivalent carbon emission and the carbon tax is credited annually to offset total OPEX.

6.5.3 Fuel Costs

- Primary fuel: The primary fuel is nuclear fuel for all SMR options and diesel for diesel generator option. Due to wide variety of refueling approaches proposed by SMR vendors, the fuel costs are calculated per core loading, and then converted to \$/MJ basis. The fuel cost is treated as annual operational expense for both nuclear and diesel options. Fuel cost per loading is calculated using a third party calculator²⁴ and has to be entered into the spreadsheet manually.
- Backup fuel: The backup fuel is diesel for all technology options.

6.5.4 Regulatory Costs

Initial site regulatory costs and license renewal costs are included. The initial site license costs are included as a CAPEX item and annual license renewal costs are treated as OPEX.

²⁴ The WISE Uranium Fuel Cost Calculator, <http://www.wise-uranium.org/nfcc.html>, last accessed January 29, 2016.

6.6 System Configurations

The cost factors that are included in the LCOE calculation in this study are shown in Table 6-1. The cost factors are discussed in detail in Section 7.2 through Section 7.4.

Table 6-1: Cost factors in LCOE calculation

LCOE Calculation Input Categories	Cost Items			
	Diesel Power Plant	Note	SMR Technologies	Note
CAPEX	Primary diesel generator		Nuclear power plant	Nth of a kind unit cost is used
	Backup diesel generator		Backup diesel generator	M+N+1 configurations used
	Unit addition		Energy storage	Flywheel is assumed to be used to control frequency
	Replacement		Initial site licensing cost	
			Spent fuel storage	
			Decommissioning	
			Core re-deployment	In case cores are re-deployable
			Unit addition	
OPEX	Diesel fuel		Nuclear fuel	
	Diesel engine rebuild	Diesel engines are assumed to be rebuilt after 30k hours	Diesel fuel	Backup fuel
			Labour cost	Includes on-site operator, security and off-site staffs
			Security	Annual security training allowance
			Insurance	Nuclear insurance cost
			Fixed O&M	Parts replacement and general upkeep
		GHG credit	Carbon tax credit is applied as a negative OPEX	

7. Initial Values for SMR Evaluation Databank

This section describes the data entries and relevant background information in the SMR Evaluation Databank.

7.1 Identification of SMRs and Initial Screening

7.1.1 Initial list of SMRs

The initial list of SMRs was compiled from various lists, articles, and databases available in the public domain, including UxC, IAEA, OECD/NEA, and the WNA. The list totals 90 different SMR technologies from developers around the globe. Appendix A presents the initial list of SMRs.

7.1.2 Screening Criteria

For the purpose of this study, a selection of SMRs suitable for northern Ontario deployment were selected from the initial list for further analysis. The screening criteria methodology is shown in Table 7-1.

Table 7-1: SMR Screening Criteria Summary

Criteria	Description
1. Nameplate Capacity The size of the SMR must be suitable to meet the load requirements of remote mines in northern Ontario. The size limitations are based on typical mine load patterns.	25 MWe
2. Vendor Credibility Only SMRs developed by credible vendors or technology owners were considered. The rationale for this is to eliminate SMR technologies from vendors that do not or are not expected to be capable of developing the framework and corporate structure necessary to be a nuclear technology license-owner in Canada.	Vendor is or possesses: <ul style="list-style-type: none"> - Significant funding or financial capability - A Government Institute or Laboratory - Tier 1 Existing Nuclear Supplier - Developed or backed by large reputable engineering company(ies)
3. Development Effort Only SMR technologies that have seen recent development are considered. This will eliminate SMR technologies that are not expected to see further development or implementation.	In the last 3 years, the SMR technology has seen one or more of the following: <ul style="list-style-type: none"> - Noticeable investor engagements - Technology developments - Media publications - White-paper publications

7.1.2.1 Size

The first criteria in screening SMR technologies is the reactors generating capacity, or size. The rationale in screening first by size is to eliminate SMRs that are far too large for the generation requirements of mines.

It should be noted that some SMRs that meet the screening criteria may still generate more power than is required. In these scenarios the reactor will have to be de-rated to run at a

lower generating capacity. This will penalize the reactors economic case in the sense that it's calculated LCOE will increase since it is not generating power at its maximum capacity, yet capital and operating costs remain the same.

7.1.2.1.1 Remote Mines

Typical power generation requirements for remote Canadian mines are presented and discussed in detail in Section 3.2.5.2. Most diesel-powered mines in northern regions experience peak loading between 10 – 40 MWe. From this range, 25 MWe was specified as the upper-limit on reactor size for consideration in remote mining applications. For scenarios when a reactor is significantly less than 25 MWe (e.g. 5 MWe), multiple reactors installed in parallel will be considered in order to meet required demands.

7.1.2.2 Vendor Credibility

Only technologies developed by credible vendors shall be considered. To be considered for the study, the vendor should be either a government institution, a crown corporation, an existing Tier 1 nuclear supplier, a large reputable engineering company (or backed by one), or possess significant funding and financial capability.

The rationale behind only considering vendors of these sorts is to eliminate technologies developed by vendors that are unlikely to see development advancement when considering business practices and financial capabilities.

7.1.2.3 Active Business and Technology Development

The technology proponent should be active in either business development and/or in R&D effort. The proponent's efforts shall be judged based on public sources, news releases, and additional internal Hatch business intelligence gathering activities. The proponent's SMR technology shall be considered if, in the last three years, the proponent has seen noticeable investor engagements, technology developments, or white paper or media publications.

7.1.3 Small Modular Reactor Shortlist

The SMR's presented in Table 7-2 pass all three screening criteria and are further investigated in this study for deployment in remote mines.

Table 7-2: Small Modular Reactor Shortlist

Reactor Name	Reactor Type
IPWR-1	Integral Pressurized Water Reactor
IPWR-2	Integral Pressurized Water Reactor
GCR-1	Gas Cooled Reactor
GCR-2	Gas Cooled Reactor
GCR-3	Gas Cooled Reactor

Reactor Name	Reactor Type
LFR	Lead Fueled Reactor
SFR-1	Sodium Fast Reactor
SFR-2	Sodium Fast Reactor
MSR	Molten Salt Reactor

7.2 Design Specific Data

The design specific data is collected from public sources, vendor surveys, and expert knowledge.

7.2.1 **Technical Descriptions**

Refer to Table 7-3 for high-level technical descriptions of the shortlisted SMR technologies.

Table 7-3: Technology Descriptions

Reactor	IPWR-1	IPWR-2	GCR-1	GCR-2	GCR-3	LFR	SFR-1	SFR-2	MSR
Coolant	Water	Water	Helium Gas	Helium Gas	Helium Gas	Lead	Heat pipes	Liquid Metal (Sodium)	Molten Salt
Gross Electrical (MWe)	6.4	9	16	5	8.4 (twin unit)	3 – 10	1.5 – 2.8	10	32.5
Fuel Type	Uranium Oxide in Silumin matrix	Oxide	TRISO	Fully Ceramic Microencapsulated (FCM) Fuel (TRISO particles in Silicon Carbide matrix)	TRISO	Uranium Dioxide Pellet	Metallic	Metallic	Molten Salt
Fuel Enrichment (%)	19.7	<20	16 – 19	12	15 – 20	19.9	5 – 20	17 – 19	Unknown
Neutron Spectrum	Thermal	Thermal	Thermal	Thermal	Thermal	Fast	Fast	Fast	Thermal
Planned Mode of Operation	Standard	Standard	Autonomous	Standard	Autonomous	Standard	Autonomous	Standard	Standard
Major Passive Safety Systems	Passive shut-off valves & destraining devices Passive design of rod drives Emergency cooling system Reactor biological shielding Safety pressure hull, containment	Negative reactivity Reactor shut down Emergency cooling system Self-activated fail-safe drives Design features preventing loss of cooling medium	Inherent safety of TRISO	Melt-down proof safety and containment of radioactive materials provided by refractory and self-containing FCM fuel Low core power density Non-radioactive He coolant Negative temperature coefficient Fully passive decay heat removal	High negative temperature coefficient of reactivity Inherent safety of TRISO Passive post-trip cooling Long system response times, simple system design, and a neutronically transparent single phase coolant Natural circulation in reactor Multiple barriers to radionuclide emission	Natural convection Conduction In situ shielding and iodine filter	Passive primary and secondary systems Pump-less design Reactor passively conducts heat to surrounding below-grade emplacement in off-nominal scenarios Reactor operates at atmospheric pressure	Passive decay heat removal system Reactor shutdown (scram) system Negative coolant temperature coefficient Low pressure system with pool design and guard vessel Large margin to coolant boiling or cladding failure Double-walled steam generator against sodium-water reaction Reactor building located on seismic isolator	Unknown
Core Redeployability	Yes	No	No	No	Possible	No	Yes, within 12-year deployment life	No	No

7.2.2 CAPEX

CAPEX data from SMR vendors is used in the analysis. In lieu of vendor's data, their capital costs are estimated using public domain data applicable to that technology.

7.3 Generic Data (Non-Nuclear)

7.3.1 GHG Emission

The province of Ontario plans to implement a cap-and-trade program similar to those existing in California and Quebec. Such a program would place a tangible cost on GHG emissions which must be accounted for when evaluating energy generation options.

7.3.1.1 Cap-and-Trade Program

The proposed program would impose a greenhouse gas emission limit that will subsequently be decreased at a specified rate annually. This limit translates to tradable emission allowances, which will be freely allocated or auctioned quarterly to emitters. Companies will also have the option to buy and sell allowances on the open market. Each allowance is typically equivalent to one metric tonne of carbon dioxide or carbon dioxide equivalent. Upon the end of each compliance period, emitters will have to surrender enough allowances to cover their actual emissions during the period. To match the decreasing greenhouse gas emission limit, the number of available allowances will decrease over time as well. Such an open market would allow for cost-effective emissions reductions and drive low-greenhouse gas innovation.

7.3.1.1.1 Ontario Cap-and-Trade Coverage

Ontario’s long-term goal is to reduce greenhouse gas emissions by 80% below 1990 levels by 2050²⁵. In order to achieve this, Ontario has set two mid-term targets of 15% below 1990 levels by 2020 and 37% below 1990 levels by 2030. Announced in April 2015, Ontario’s cap-and-trade system will help meet these targets and is scheduled for implementation on January 1, 2017. Ontario intends to link its system with those existing in Quebec and California.

Ontario’s cap will decline at a rate of 4.7% per year in order to meet the 2020 target, although different sectors and types of emissions could face varying rates of decline²⁶. The province also intends to align with the Quebec-California three-year compliances periods post-2020.

In alignment with the Quebec program, the Greenhouse Gases (GHG) likely to be covered by the Ontario program, as well as their respective Global Warming Potentials (GWPs), are listed in Table 7-4. GWP is a concept which allows the comparison of the ability of each greenhouse gas to trap heat in the atmosphere relative to carbon dioxide over a specified duration²⁷.

Table 7-4: Types of GHGs subject to Cap-and-Trade Regulation²⁸

Greenhouse Gas	Global Warming Potential
Carbon Dioxide (CO₂)	1
Methane (CH₄)	21
Nitrous Oxide (N₂O)	310
Hydrofluorocarbons (HFC)	12 to 11,700
Perfluorocarbons (PFC)	6,500 to 9,200
Sulfur Hexafluoride (SF₆)	23,900
Nitrogen Trifluoride (NF₃)	17,200

The cap-and-trade system in Ontario will limit the allowances that are distributed for free to the emitters covered by the system. It proposes mechanisms that promote internal CO₂e emission reductions, and enables the transfer of CO₂e credits generated by real CO₂e emission reductions to and from covered and not-covered facilities. The ultimate target of the system will be to achieve real GHG emission reductions at the lowest cost possible for the covered facilities.

The Ontario cap-and-trade program will cover both combustion and fixed process emissions. The definitions of these emissions are as follows:

²⁵ Ontario’s Climate Change Strategy, Ministry of Environment and Climate Change, 2015

²⁶ O. Reg. 144/16: The Cap and Trade Program filed May 19, 2016 under Climate Change Mitigation and Low-Carbon Economy Act, 2016, S.O. 2016, c.7

²⁷ Global Warming Potentials, Environment and Climate Change Canada, <https://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=CAD07259-1>

²⁸ Appendix A.1, *Regulation respecting the mandatory reporting of certain contaminants into the atmosphere (Q-2, r. 15)*, Government of Quebec, September 1, 2012.

- **Combustion** sources cover the exothermic oxidization of a fossil fuel to generate heat. It is possible to reduce these emissions with more efficient technologies and fuel switching.
- **Fixed process** sources cover emissions from industrial processes involving chemical or physical reactions (other than combustion), where the primary purpose of the process is not energy production.

The program will ensure that combustion emissions and fixed process emissions are reported separately.

The current proposed sector coverage in Ontario includes:

- Electricity (including imported electricity) → covered at fuel distributor level.
- Industrial and large commercial (e.g., manufacturing, base metal processing, steel, pulp and paper, food processing) → annual GHG emissions equal to or greater than 25,000 tonnes.
- Institutions → annual GHG emissions equal to or greater than 25,000 tonnes.
- Transportation fuel (including propane and fuel oil) → covered at distribution level, at volumes of 200 litres or more.
- Distribution of natural gas (e.g., heating fuel) → annual GHG emissions equal to or greater than 25,000 tonnes.

7.3.1.1.2 Linkage

The Ontario cap-and-trade program will eventually be linked to existing programs in California and Quebec. As such, the Ontario allowance prices were calculated by escalating the current prices in these existing markets.

California:

Launched on January 1, 2013, the California Cap-and-Trade Program imposes a greenhouse gas emission limit that decreased by approximately 2% annually from 2013 to 2015, and will decrease by approximately 3% annually from 2015 through 2020²⁹.

Quebec:

To date, Quebec is the only other jurisdiction in the Western Climate Initiative that has linked their cap-and-trade program to California's. As of January 1, 2014, greenhouse gas emission allowances from California and Quebec are interchangeable and can be traded across jurisdictions³⁰.

²⁹ California Cap-and-Trade Program Summary, Center for Climate and Energy Solutions, January 2014

³⁰ Western Climate Initiative, Quebec, <http://www.mdelcc.gouv.qc.ca/changements/carbone/WCI-en.htm>

7.3.1.2 Carbon Cost

A minimum price level for allowances is set through an auction reserve price. This ensures that low-carbon innovation will continue to have market value. In addition to this, maintaining a strategic reserve of allowances maintains the price of carbon within a stable range.

In the joint Quebec-California market, the auction reserve price was set at \$10 per tonne CO₂e in 2013 and escalated annually at 5% plus inflation and converted to Canadian currency. The latest auction reserve price issued on December 1, 2015, for the 2016 year was \$12.73 USD³¹. Quebec's 2016 auction reserve price was calculated using an inflation rate of 1.09%. Ontario plans to align its reserve price with the Quebec-California market price for 2017. Assuming a conservative 2% annual inflation rate for Ontario, the 2019 auction reserve price should be approximately \$15.01 USD. Using the 25-year average USD/CAD exchange rate of around 0.7967 USD/CAD, this equals \$18.84 CAD.

It is proposed that 5% of total allowances from the cap each year would be set aside in the strategic reserve, with price tiers again aligned with the joint Quebec-California market for 2017. In this market, the price tiers were set at \$40, \$45, and \$50 USD per allowance in 2013 and escalated annually at 5% plus inflation and converted to Canadian currency.

The latest carbon market price, as of January 14, 2016, was \$13.21 USD per tonne CO₂e³². The price of carbon has remained fairly stable in the past several years, with highs and lows ranging from just over \$16 USD in January 2013 to just under \$12 USD in November 2013.

As per Hatch internal data, a diesel intensity factor of 2.79 kg CO₂e/L diesel was used to calculate the carbon costs of an all-diesel generating facility as well as the avoided carbon costs arising from the replacement of said diesel facility with each SMR technology being evaluated. The resultant carbon costs were calculated in terms of \$/kg CO₂e.

7.3.2 Long-Term Diesel Price

The long-term diesel price forecast used in this study is based on the forecasted crude oil price trend as presented in the EIA's Annual Energy Outlook 2015 (with projections to 2040) and the average annual 2015 rack price of diesel in Thunder Bay as presented in Table 7-5. As mentioned in the EIA's Annual Energy Outlook, changes in gasoline and diesel fuel oil prices generally move in the same direction as changes in the global crude oil price. For the purpose of this study it is assumed that diesel price trends will follow crude oil price trends proportionately. In 2015, the average crude oil price was US\$50.75 per bbl. The cost of delivered diesel is calculated from the Thunder Bay rack price plus taxes and an additional cost added to account for transportation via air and road

³¹ California Cap-and-Trade Program and Quebec Cap-and-Trade System, 2016 Annual Auction Reserve Price Notice, December 1, 2015.

³² California Carbon Dashboard, <http://calcarbondash.org/>

Table 7-5: Forecasted Long Term Diesel Price

Diesel Delivery Location	2015	2020	2030	2040
Remote Mines (\$/L)	0.99	1.38	1.79	2.39

7.3.3 Diesel Engine Lifecycle Cost

Hatch's in-house knowledge and expertise is used to estimate the diesel engine lifecycle cost. For small diesel reciprocating engines, an initial CAPEX of \$500/kW and non-fuel O&M cost of \$60/MWh are used. The small diesel engines typically have a 30,000 hour operating lifetime after which they need to be replaced. For medium-speed engines that are typically used in mining applications, an initial CAPEX of \$2,000/kW and non-fuel O&M cost of \$15/MWh are used. The O&M cost for medium-speed engines include periodic re-build costs.

7.3.4 Flywheel cost

Based on a past Hatch project for mining power systems, SMRs alone may not be able to provide the AC-frequency in a captive mining power system due to large reactive load fluctuations. It is expected that a microgrid controller will have to be installed with a fast acting energy storage system. While the selection of an energy storage technology is another subject of discussion, this study assumes that flywheels are used to compensate up to 50% of an SMR unit output. Without considering the lifetime operating cost, the capital cost of US\$350/kW is added to the initial SMR capital cost.³³

7.3.5 Cost Escalation (CPI)

In the LCOE calculation, Canadian CPI inflation index³⁴ is applied to the costs that occur in the future operations, including decommissioning costs, salaries, crude oil prices and other capital and non-capital costs.

7.3.6 Currency and Exchange Rate

All costs are in 2016 Canadian Dollars. When the vendor-provided cost information and other commodity prices are in US Dollars, the currency is converted to Canadian Dollars using 25-year monthly average exchange rates (from January 1990 to December 2015) between CAD and USD as published by Statistics Canada³⁵.

The average USD to CAD rate is 1.25517139.

³³ Calculated from 2003\$ Capital Cost Estimate from State Utility Forecasting Group <https://www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/SUFG%20Energy%20Storage%20Report.pdf>

³⁴ Statistics Canada, <http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/cpis01a-eng.htm>, last accessed on January 26, 2016.

³⁵ Statistics Canada, CANSIM Table 176-0064, <http://www5.statcan.gc.ca/cansim/pick-choisir?lang=eng&p2=33&id=1760064>, last accessed on January 26, 2016.

7.4 Generic Data (Nuclear)

7.4.1 Security Staff Complement

The security needs for an SMR operating in a remote area have been discussed by the stakeholders at fundamental levels. There are several counter-balancing elements in an SMR security equation for remote areas. On the negative side, there are the financial and logistical challenges in maintaining a large on-site security force, as well as the long travel time for an off-site response team to reach the site in response to an emergency situation. These make the human action-based resistance to a sabotage attempts more difficult. On the positive side, the remoteness of the plant also introduces transportation and logistical challenges to potential malicious parties.

The security at a nuclear facility can be provided by a combination of engineered systems and human-based solutions. The actual security measures for an SMR in remote operation will depend on a site and design specific threat and risk assessment, as well as the security plan to meet the requirements outlined in the Canadian Nuclear Security Regulation³⁶. The regulations are enabled by the Nuclear Safety and Control Act³⁷, and are consistent with the Nuclear Security Fundamentals, Recommendations, Implementing Guides and Technical Guides³⁸. The relevant IAEA documents are:

- Nuclear Security Fundamentals: IAEA Nuclear Security Series No.20: Objective and Essential Elements of a State's Nuclear Security Regime.
- Technical Guidance: IAEA Nuclear Series No.4: Engineering Safety Aspects of the Protection of Nuclear Power Plants against Sabotage.
- Recommendations:
 - ◆ IAEA Nuclear Security Series No. 13: Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5).
 - ◆ IAEA Nuclear Security Series No. 14: Nuclear Security Recommendations on Radioactive Material and Associated Facilities.
 - ◆ IAEA Nuclear Security Series No.15: Nuclear Security Recommendations on Nuclear and Other Radioactive Material out of Regulatory Control.

Based on the Canadian Nuclear Security Regulations, the CNSC has published the following regulatory documents and guidance to assist licensees:

³⁶ Nuclear Security Regulations (SOR/2000-209), <http://laws.justice.gc.ca/eng/regulations/SOR-2000-209/>, last accessed on January 4, 2016.

³⁷ Nuclear Safety and Control Act (S.C.1997, c.9), <http://laws.justice.gc.ca/eng/acts/N-28.3/>, last accessed on January 4, 2016.

³⁸ IAEA Nuclear Security Series, http://www-ns.iaea.org/security/nuclear_security_series.asp, last accessed on January 4, 2016.

- Criteria for Physical Protection Systems and Devices at High-Security Sites (RD-321).
- Criteria for Explosive Substance Detection, X-ray Imaging, and Metal Detection Devices at High-Security Sites (RD-361).
- REGDOC-2.12.1, High-Security Sites: Nuclear Response Force.
- REGDOC-2.12.2, Site Access Security Clearance.
- REGDOC-2.12.3, Security of Nuclear Substances: Sealed Sources.
- Entry to Protected and Inner Areas (G-205).
- Transportation Security Plans for Category I, II or III Nuclear Material (G-208).
- Security Programs for Category I or II Nuclear Material or Certain Nuclear Facilities (G-274).

For the purpose of this study, the minimum security complement at a remote SMR operation site is estimated to be 10 based on the following observations in the Nuclear Security Regulation:

- Since the SMRs considered in this study will be using enriched uranium fuel with enrichment between 10% and 20% and initial fissile quantities in orders of hundreds of kilograms, the nuclear materials at these SMR facilities are classified as Category II nuclear materials. The category definition is reproduced from the regulation in Figure 7-1.

SCHEDULE 1
 (Section 1)

CATEGORY I, II AND III NUCLEAR MATERIAL

Item	Column 1 Nuclear Substance	Column 2 Form	Column 3 Quantity (Category I) ¹	Column 4 Quantity (Category II) ¹	Column 5 Quantity (Category III) ^{1,5}
1.	Plutonium ²	Unirradiated ³	2 kg or more	Less than 2 kg, but more than 500 g	500 g or less, but more than 15 g
2.	Uranium 235	Unirradiated ³ — uranium enriched to 20% ²³⁵ U or more	5 kg or more	Less than 5 kg, but more than 1 kg	1 kg or less, but more than 15 g
3.	Uranium 235	Unirradiated ³ — uranium enriched to 10% ²³⁵ U or more, but less than 20% ²³⁵ U	N/A	10 kg or more	Less than 10 kg, but more than 1 kg
4.	Uranium 235	Unirradiated ³ — uranium enriched above natural, but less than 10% ²³⁵ U	N/A	N/A	10 kg or more
5.	Uranium 233	Unirradiated ³	2 kg or more	Less than 2 kg, but more than 500 g	500 g or less, but more than 15 g
6.	Fuel consisting of depleted or natural uranium, thorium or low-enriched fuel (less than 10% fissile content) ⁴	Irradiated	N/A	More than 500 g of plutonium	500 g or less, but more than 15 g of plutonium

¹ The quantities listed refer to the aggregate of each kind of nuclear substance located at a facility, excluding the following (which are considered separate quantities):

- (a) any quantity of the nuclear substance that is not within 1 000 m of another quantity of the nuclear substance; and
- (b) any quantity of the nuclear substance that is located in a locked building or a structure offering similar resistance to unauthorized entry.

² All plutonium except that with isotopic concentration exceeding 80% in plutonium 238.

³ Material not irradiated in a reactor or material irradiated in a reactor but with a radiation level equal to or less than 1 Gy/h at 1 m unshielded.

⁴ Other fuel that by virtue of its original fissile content is classified as Category I or II before irradiation may be reduced one category level while the radiation level from the fuel exceeds 1 Gy/h at 1 m unshielded.

⁵ Quantities less than the quantities set out in column 5 for Category III nuclear material and any quantities of natural uranium, depleted uranium and thorium should be protected at least in accordance with prudent security practice.

SOR/2006-191, ss. 33, 34(F), 35, 36, 40(F).

Figure 7-1: Nuclear material category definition in the Canadian Nuclear Security Regulations

- Nuclear security regulation section 15(2)(e) which is applicable to Category II materials requires that a security monitoring room shall be ‘attended at all times by at least one nuclear security officer.’
- Regulation section 30 reads that ‘Every licensee shall at all times have available at a facility at which it carries on licensed activities a sufficient number of nuclear security officers to enable the licensee to comply with this Part and do the following: (control the movement of persons, materials and land vehicles; (b) conduct searches of persons, materials and land vehicles for weapons, explosive substances and Category I, II or III nuclear material; conduct preventative foot and land vehicle patrols of the facilities and the perimeter of the protected area to inspect for security breaches and vulnerabilities; (d) response to and assess alarm incidents; (e) apprehend and detain unarmed intruders; (f) observe and report on the movements of armed intruders; and (g) operate security equipment and systems.’

- The regulation section 32 reads that ‘Every licensee shall at all times maintain an onsite nuclear response force that is capable of making an effective intervention, taking into account the design basis threat and any other credible threat identified by a threat and risk assessment.’

Therefore, while the regulation does not specify the upper limit for the number of security officers, it dictates the theoretical minimum number to be two, one in a security monitoring room and another to conduct preventative and responsive activities. Based on 3 shift schedule with 5 rotating teams, this study assumed ten security staff to be the minimum complement.

7.4.2 Additional Security Cost

The Nuclear Security Regulation also requires that every licensee shall arrange an off-site response. Section 35 dictates that annual familiarization visits to the facility are made by members of the off-site response force. In section 36, at least one security exercise is held every two years to test the effectiveness of the contingency plan and of the physical protection system. To compensate for these costs, annual security training allowance of \$500,000 is assumed per site in this study.

7.4.3 Non-Proliferation Compliance

In this study, it is assumed that all designs can potentially meet these regulations. The inherent technology limitations to meet the regulatory requirements are qualitatively assessed. The following documents are relevant to the non-proliferation aspects of SMRs:

- CSA Standard N290.7, Cyber-security for nuclear power plants and small reactor facilities.
- CNSC Regulatory Document: Accounting and Reporting of Nuclear Material (RD-336).
- CNSC Regulatory Document: Guidance for Accounting and Reporting of Nuclear Material (GD-336).
- CNSC Regulatory Document: REGDOC-2.13.2, Import and Export (in draft).

7.4.4 Staffing Complement Requirement

Another major area of interest in SMR economics is the staff complement requirement applicable to small power reactors. Since these reactors are proposed to operate in remote areas, it is difficult to assure the availability of local skilled workers. Also, smaller amounts of power are produced by these reactors such that any small increase in labour costs will have a significant impact on reactor economics. Therefore, SMR vendors aim to reduce the staff complements to the minimum levels.

The IAEA technical document³⁹ lists the following design approaches to reduce staffing:

- Design simplification.
- Passive safety systems.
- Reduction in systems, structures, and components (especially safety grade).
- Component standardization.
- Use of proven technology.
- Use of equipment requiring less maintenance.
- Improved equipment maintenance access.
- Increased control and diagnostic automation.
- Improved human-machine interface.
- Use of digital I&C.
- Use of modern information management systems.
- Utility involvement in the design process.

Assuming that the proposed SMRs incorporate the above approaches in their designs, the minimum staff complement is established. In this study, the on-site staff and corporate staff are separately estimated to account for the operating practices proposed by SMR vendors. That is, several SMRs sites will be served by shared corporate resources such as administration, engineering, maintenance, refueling teams and site services.

7.4.4.1 *Zero On-site Staff Complement Condition*

Some SMR vendors claim that they plan to operate the plants remotely without any on-site operators. While this study did not consider zero on-site staff in the financial analysis, the possibility of having zero operators is examined briefly here.

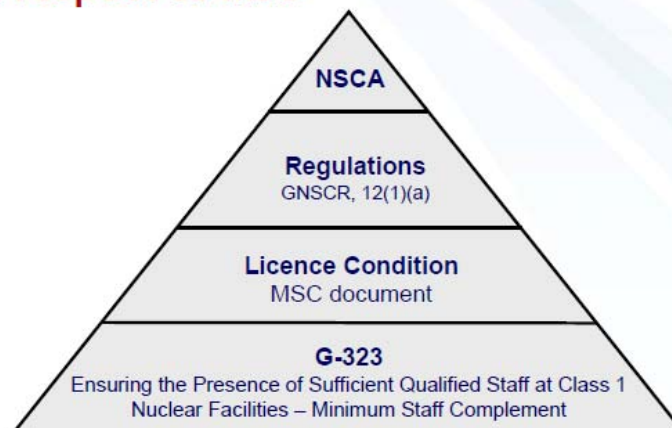
The actual calculation of minimum staff complement (MSC) is a complex task requiring a systemic analysis based on events identified in safety reports (including single and multi-unit station cases), credited operator actions, credible events in the PSA, emergency operating procedures and operating strategies. The Canadian regulatory framework for determining the MSC is shown in Figure 7-2.

³⁹ International Atomic Energy Agency, Staffing requirements for future small and medium reactors (SMRs) based on operating experience and projections, IAEA-TECDOC-1193, January 2001.

The minimum requirement is provided in the General Nuclear Safety and Control Regulations⁴⁰ 12 (1)(a) as follows: licensees shall “ensure the presence of a sufficient number of qualified workers to carry on the licensed activity safely.” In regulatory guidance document⁴¹, the above requirement is further refined as follows: “It is expected that the minimum staff complement requirements are validated by the licensee to provide assurance that there is, at all times, a sufficient number of qualified workers available to operate the facility safely and to respond to the most resource-intensive conditions under all operating states, including normal operations, anticipated operational occurrences, design basis accidents, and/or emergencies.”

Therefore, the regulatory condition for having zero on-site staff is the inversion of the above paragraph: i.e., a licensee can claim to have zero on-site staff if it can be demonstrated that the plant does not require any personnel presence to ensure the facility safety in design basis accidents and emergency conditions.

CNSC’s Regulatory Framework with respect to MSC



Canadian Nuclear Society

June 7, 2011 - 7

⁴⁰ General Nuclear Safety and Control Regulations (SOR/2000-202), accessible at <http://laws-lois.justice.gc.ca/eng/regulations/sor-2000-202/index.html>

⁴¹ Canadian Nuclear Safety Commission, Regulatory Guide G-323, *Ensuring the Presence of Sufficient Qualified Staff at Class I Nuclear Facilities – Minimum Staff Complement*, http://nuclearsafety.gc.ca/pubs_catalogue/uploads/G-323_e.pdf, last accessed on January 27, 2016.

Figure 7-2: CNSC Regulatory Framework with respect to Minimum Staff Complement⁴²

7.4.4.2 Operator Estimates

The operator requirement is estimated using the benchmark data points extracted from an IAEA report⁴³. A non-linear curve was fitted to the data using the following constraints:

- For the smallest reactor, 1 operator per shift is assumed. In addition, 3 shifts and 5 rotating teams are assumed to reassure the operator availability at all times. Thus, the minimum number of operators was assumed to be 5 per site regardless of the plant size.
- The number of operators per MW should be higher for small power plants but it should decrease for larger plants due to the economies of scale effect.

These constraints indicate that the best fitted curve should resemble a parabolic function with a shifted x-axis. A best fitted function was selected based on regression analysis and it was determined to be a Weibull Model. Figure 7-3 shows the result.

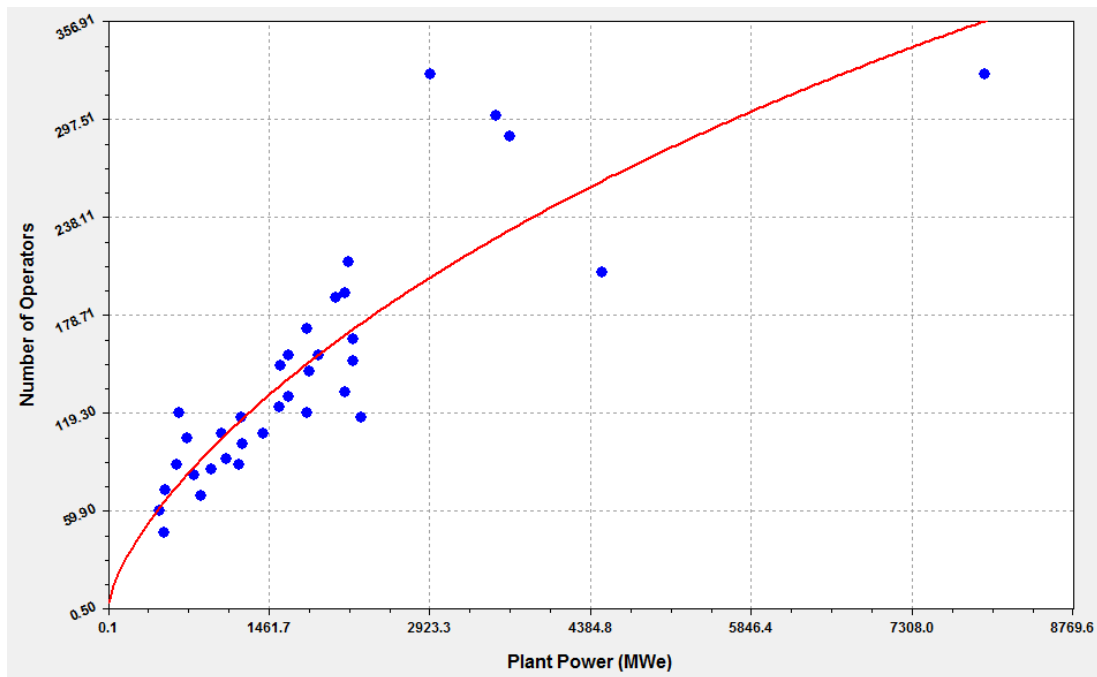


Figure 7-3: Operator requirement for nuclear power plants

The Weibull Model is described by the following function:

$$\text{Number of Operators} = a - b \times e^{-c \times (\text{Reactor Power in MWe})^d}$$

⁴² S. Dolecki & H. McRobbie, Minimum Staff Complement Safety in Numbers, Presentation at Canadian Nuclear Society Conference, Niagara Falls, June 7, 2011.

⁴³ International Atomic Energy Agency, Nuclear Power Plant Organization and Staffing for Improved Performances: Lessons Learned, IAEA-TECDOC-1052, Vienna, 1998.

Where the coefficients are $a=7.858E+002$, $b=7.815E+002$, $c=9.153E-004$ and $d=7.222E-001$.

7.4.4.3 *Corporate Functional Staff Estimates*

Another staffing requirement in SMR economics is corporate staff such as administration and engineers, and an off-site team who will be travelling to sites to provide various functions on a part-time basis. These functions include:

- Maintenance: construction support, maintenance, planning, outage craft, outage management, scheduling.
- Engineering: computer engineering, drafting, engineering design, plant engineering, engineering programs, technical engineering, nuclear fuels, procurement engineering, project management, reactor engineering.
- Safety: ALARA, chemistry, emergency preparedness, environmental, HP applied, HP support, licensing, nuclear safety, QA, QC/NDE, rad waste/decon/plant cleaning, safety/health.
- Support: Administration, budget/finance, clerical, communications, contracts, document control, human resources, information systems, management, management assistance, materials management, purchasing, training, warehouse.
- Site Services: Civil/community services, employee housing, facility maintenance/non-plant cleaning, fire protection, offsite high and low-level waste disposal, security.

The data points for maintenance, engineering, safety, support and site services staff are extracted from an IAEA report⁴³ and are linearly extrapolated towards zero plant power output. Then, the required staff numbers for SMRs are estimated based on the assumption that the same staff can support up to 10 different sites. It is assumed that site services only require 50% of the staff since local resources are likely to be utilized. Also, support staff are not included in the study since they are excluded in the diesel power economic assessment.

7.4.5 *Decommissioning*

Decommissioning costs are estimated based on background information regarding OPG's nuclear waste management and decommissioning activities at Pickering A and B Generating Stations, Darlington Generating Station, and the Bruce Generating Station⁴⁴. A value of actual contributions towards decommissioning made to the Ontario Nuclear Funds by OPG and the province of Ontario in 2003 was escalated by 5.15% annually until 2016. Using this escalated value of just under \$6,887 million, as well as nameplate ratings of the aforementioned generating stations, a decommissioning cost of approximately \$534.8/kWe was calculated. This value was then used to estimate the decommissioning costs of the SMR technologies under evaluation based on their specific nameplate ratings.

⁴⁴ OPG, Nuclear Waste Management and Decommissioning – Background Information, May 26, 2010.

7.4.6 Nuclear Fuel Waste Management

The Nuclear Fuel Waste Act (NFWA) requires the establishment of trust funds by each waste owner to ensure secure financing is available for waste management activities. The Nuclear Waste Management Organization (NWMO) identifies in their 2014 Annual Report⁴⁵ the trust fund balance and amount of waste owned for each waste owner in Canada. Based on these figures, an approximate cost of waste management fund allocation can be estimated based on \$/kg of waste or \$/kWh of energy produced, as shown in Table 7-6.

Table 7-6: Estimated Waste Management Costs in Canada

Waste Owner	\$M	Total Bundles	kg-HM	TWh produced	¢/kWh	\$/kg-HM
AECL	45	32,658	653,160	42	0.11	\$68.90
NB Power	125	129,941	2,598,820	166	0.08	\$48.10
Hydro-Quebec	119	127,450	2,549,000	162	0.07	\$46.68
OPG	3,114	2,221,256	44,425,120	2,832	0.11	\$70.10
All	3,403	2,511,305	50,226,100	3,202	0.11	\$67.75

The waste management cost calculations are based on a rounded average of 20 kg of heavy metal per fuel bundle, an average burn-up of 200 MWh/kgU, and a plant thermal efficiency of 32%.

Since SMR fuel is enriched, the mass of spent fuel is expected to be much lower than that of CANDU spent fuel. On the other hand, the SMR spent fuel will likely to be more active than CANDU spent fuel. Thus, waste management costs based on mass will be unjustifiably low. Therefore, waste management costs based on \$/kWh are used in this study.

7.4.7 Fuel Cycle Cost

The SMRs for remote application use low-enriched uranium and exotic fuels (e.g., non-oxide fuel). Thus, their fuel cycle cost is expected to be higher. The fuel costs are estimated based on a once-through cycle and long-term prices of uranium and fuel processing services.

7.4.7.1 Uranium oxide concentrate price

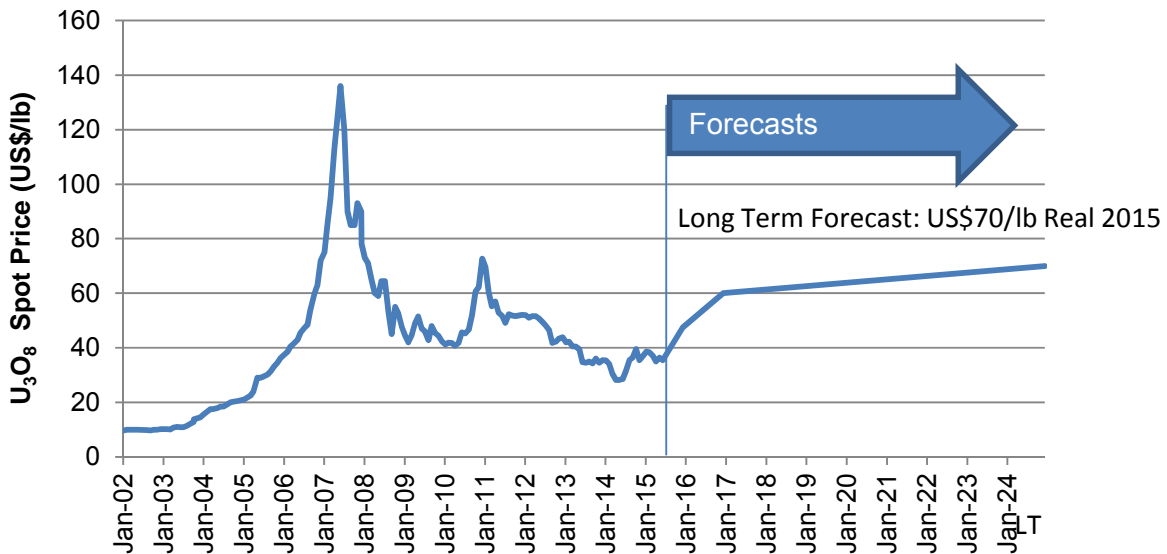
The long-term uranium oxide concentrate price is assumed to be USD\$70/lb. This is based on the median of fifteen broker forecasts from two sources made between December 2014 and April 2015 as shown in Table 7-7. The median is used in this case to eliminate any outliers.

⁴⁵ NWMO Annual Report: 2014, <https://www.nwmo.ca/en/More-information/News-and-Activities/2015/11/06/15/45/NWMO-Annual-Report-2014>, last accessed on January 26, 2016.

Table 7-7: Uranium Price Forecasts (USD\$/lb)

Date	Firm	Source	2015	2016	2017	Long Term
12/22/2014	Broker 1	CIBC	40	60	75	75
12/18/2014	Broker 2	CIBC	30.7	41.9	-	75
12/16/2014	Broker 3	CIBC	39	-	-	60
12/16/2014	Broker 4	CIBC	47.4	56	64.6	61.2
12/16/2014	Broker 5	CIBC	56	58	61	-
12/15/2014	Broker 6	CIBC	36	44.5	60	70
12/15/2014	Broker 7	CIBC	35	39	44	60
12/15/2014	Broker 8	CIBC	43	45	55	70
12/15/2014	Broker 9	CIBC	48	58	70	66
12/15/2014	Broker 10	CIBC	40	40	40	65
12/15/2014	Broker 11	CIBC	43	53	60	70
12/15/2014	Broker 12	CIBC	35	40	55	70
12/12/2014	Broker 13	CIBC	33	43	-	55
12/5/2014	Broker 14	CIBC	39.5	53	63.8	70
4/28/2015	Cantor	Cantor	41.1	50	60	80
Median			40	48	60	70

Figure 7-4 shows the historical and projected long-term U₃O₈ price. This price is used to forecast the SWU price in the model. Since this project is modeled to operate as a tolling facility, the yellowcake is not currently considered a cost to the facility nor is it considered in the working capital calculation.



Source: The Ux Consulting Company, LLC

Figure 7-4: Historical U₃O₈ Spot Price

7.4.7.2 Conversion price

The long-term conversion price is assumed to be USD\$16/kg U. Analysis has shown that the long-term conversion price changes independently from other services or products. It is noted that a significant relationship does not exist between the long-term conversion price and the short-term conversion price, spot SWU price, or the spot U3O8 price as shown in Figure 7-5. Thus, current long-term pricing adjusted for inflation has been used in the study.

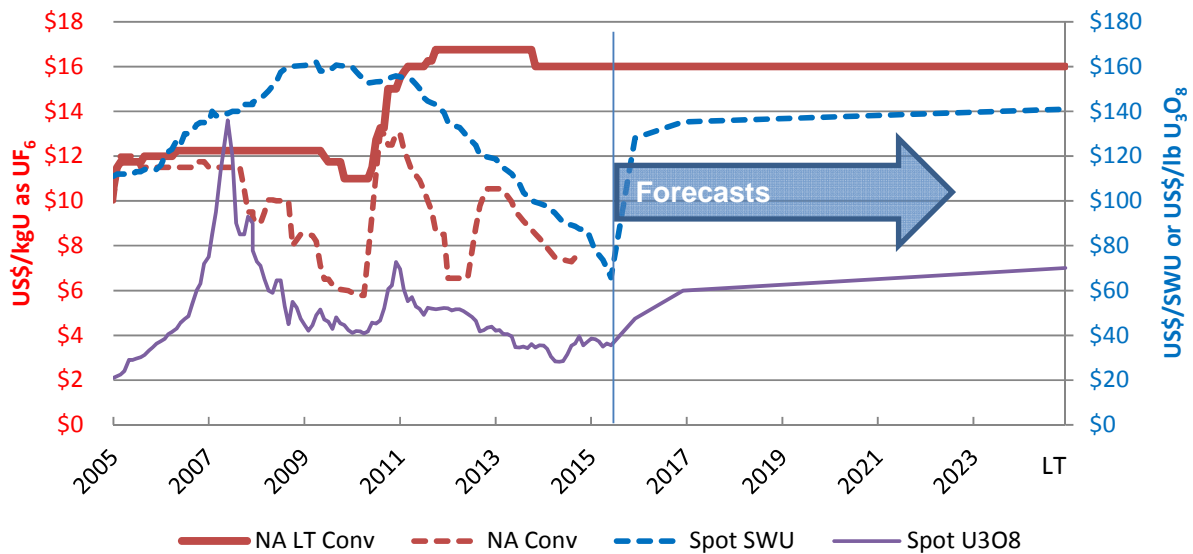


Figure 7-5: Selected Historical Price Comparisons

7.4.7.3 Enrichment price

SWU pricing is calculated from the linear trend line fitted to the historical U3O8 spot price versus SWU spot price from January 2002 to October 2015. The long term U3O8 price of USD\$70/lb is applied as the input to the equation shown in Figure 7-6, yielding the long-term SWU price of USD\$141/SWU.

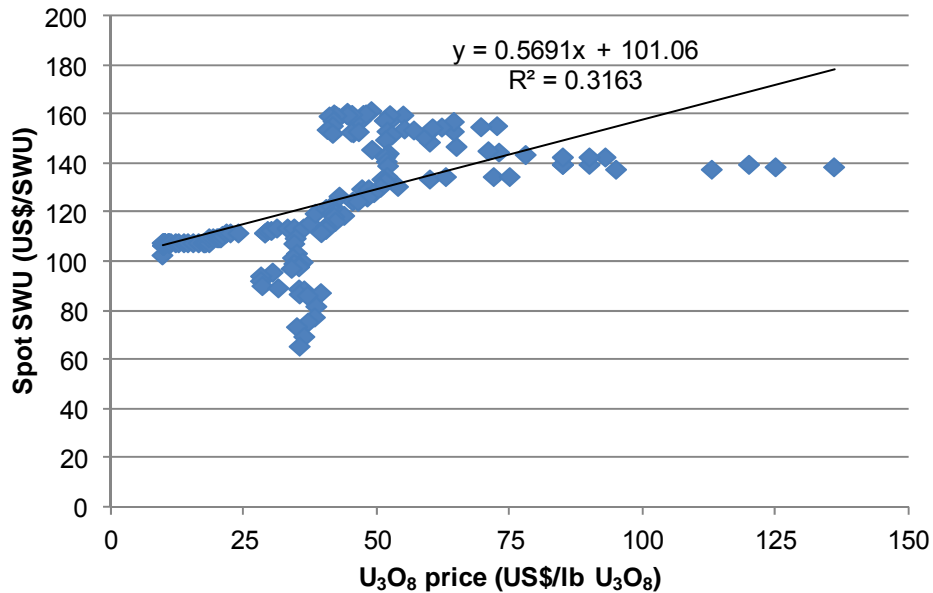


Figure 7-6: U3O8 vs. SWU Price

7.4.7.4 Fuel Fabrication Price

Unless SMR vendors provided the costs in their responses to the vendor survey, the INL study⁴⁶ on advanced fuel cost is used to establish the source for fuel fabrication costs. The reference values are shown in Table 7-8. Given the high uncertainty in the advanced fuel cycle, the costs in the report are not adjusted further. It is assumed that all fuel is low-enriched uranium.

Table 7-8: Fuel fabrication cost input values

Fuel type	Fabrication cost (USD per kg)	Note
Low enriched oxide fuel	\$270	
TRISO	\$10,000	Assumed that the fuel compact and block fabrication costs are included.
Ceramic pelletized of VIPAC fast reactor fuel	\$4,000	
Metallic fuel	\$718	Assumed to be applicable to cercer, cermet and inert matrix fuel

7.4.8 Spent Fuel Storage Cost

The SMRs which do not use the concept of the factory fuelled and sealed core that is transported to the deployment site will require on-site spent fuel storage. Since water

⁴⁶ Shropshire et al., Advanced Fuel Cycle Cost Basis, INL/EXT-07-12107, April 2007.

availability and potential environmental restrictions in remote location are uncertain, this study assumes that dry storage will be used.

To estimate the levelized unit cost for dry storage, several factors need to be considered. These factors include the initial capital, the annual operating expenses over the duration of the interim storage (until shipped for disposal or reprocessing), the total amount of electricity produced by the reactor, and the total tonnes of spent fuel consumed and cooled. Without going into details, this study adapted the cost estimated from the 2007 advanced fuel cycle cost study⁴⁶ which was between US\$100/kg (low case) to US\$300/kg (high case). Since the facility cost is expected to be high in remote areas, the high value is assumed in this study. The cost is converted to 2016 Canadian dollars to yield \$425.30/kg.

7.4.9 Insurance Cost

The nuclear insurance cost is estimated to be 0.024 cents (2009 \$) per kWh of nuclear generation, according to the analysis of the Canadian Nuclear Liability and Compensation Act by the Greenpeace⁴⁷ in 2009. This amount is based on a \$650 million liability limit. Per MW basis, it amounts to \$1,863 per MWe. By applying the Canadian CPI inflation published by Statistics Canada⁴⁸, this amounts to \$2,162 per MWe in 2016 dollars.

7.4.10 Licensing Cost

The regulatory licensing cost is expected to be a significant factor in SMR economics. The licensing cost includes CNSC staff fees, environmental assessment costs, and various public engagement process costs. In an unclassified CNSC communication document⁴⁹ with Chalk River Laboratories, the CNSC indicated that \$100M to \$150M are the estimated overall costs for regulatory activities of a fast reactor facility from receipt of the initial application to turnover and commercial operation.

Another consideration in licensing cost estimation is that the CNSC uses precedent-based licensing practices. Therefore, for an NOAK SMR with standard design, the licensing cost is expected to decrease after the first unit.

In this study, \$75 million is used as the hypothetical initial site licensing cost for a nth-of—kind reactor. Also, the licensing renewal cost of \$500,000 every 5 years is assumed. The cost is treated as an annually incurring cost of \$100,000.

⁴⁷ Gordon R. Thompson, *The Nuclear Liability and Compensation Act: Is it appropriate for the 21st century?*, Institute for Resource and Security Studies, November 2009.

⁴⁸ <http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm>, last accessed on January 26, 2016.

⁴⁹ Unclassified CNSC Communication Letter, File No: 2.01 / E-Docs No.: 4894852

8. Results

8.1 Technology Suitability Evaluation

Several trends are noticeable from the technology suitability evaluation. In general, most reactors score high on criteria related to safety, security, and environmental friendliness due to licensing regulations and requirements. As expected, all technologies are somewhat lacking in criteria related to economics, although it should be noted that the baseline criteria used for economics was in comparison to large NPPs. For further details on the economic feasibility, refer to Section 8.3.

It should be noted that it is difficult for a reactor to score equal to or greater than the reference reactor, as some of the desired features are self-conflicting. For example, modularized construction, fuelled core transportation, and plant pre-fabrication are beneficial in regards to construction and deployment time. However, it is beneficial for a reactor to be unfueled during transport, and beneficial to be difficult or impossible transport the reactor after installation for non-proliferation and security reasons. Unfortunately, these preferred beneficial features are sometimes in conflict with modular construction and easily transportable features of SMRs. A similar scenario is that above-ground construction is desired due to northern Ontario permafrost conditions; however, underground construction is desired for increased security.

In regards to deployability at site, most reactor technologies expect very short deployment and/or construction times, significantly less than expected by Hatch. However, information on overall EPC time was mostly unavailable or unknown. Reactors designed for above-ground operation are also preferred due to site-specific civil considerations such as permafrost.

In general, high-temperature gas-cooled reactors score relatively high for application in remote mines. Water-cooled reactors score average-to-high overall. Molten salt and some fast reactors are generally lacking in suitability for deployment in remote mines.

Evidently all reactors have strengths and weaknesses when considering deployment at remote mines. A likely reason for some reactors scoring well is due to application-specific designs, such as being specifically designed for deployment in northern Canadian sites or being designed for small-scale local power generation, both of which are desired features for remote mines.

8.2 Technology Deployment Potential Evaluation

8.2.1 *Technology Readiness Level*

The technology readiness evaluations of the nine shortlisted SMR technologies, specifically relating to the previously identified TRAs have been analyzed.

Technology readiness, being a measure of technology maturity, naturally favours existing and proven technologies, followed by emerging technologies with significant proof of operation and functionality, and finally conceptual or experimental technologies.

As expected, water-cooled reactors have been identified as being the most mature and the technology closest to realizing first-of-a-kind deployment. Virtually all commercially-operating, power-producing nuclear reactors are water-cooled. Thus providing substantial operating experience and well-developed knowledge of the technology.

High-temperature gas-cooled (HTGR) reactors generally score high overall due to significant and various experimental proof of operability at system and component level. Fast reactors generally are not as developed and advanced as HTGRs, however score similarly in some categories depending on the specific technology.

If vendors have conducted experiments or demonstrations of certain technology components or systems but were unwilling to disclose this information with Hatch, the score could be underrepresented in this evaluation and could warrant a re-evaluation once information is available.

8.2.2 Vendor Readiness Level

The vendor readiness evaluations of the nine shortlisted SMR technologies have been analyzed.

Naturally, the highest scoring vendors are those who currently operate or have previously operated nuclear reactors or facilities, developed nuclear technologies, or both. Secondly, large corporations or technology developers backed by large corporations score high on the vendor readiness evaluation due to credibility, financial status, and proven success in business development and management. Smaller companies relying on funding from venture capitalists or still seeking funding generally score lowest.

All vendors but one have scored 1 in “Regulatory Approval Status”, as all but one have any completed or in-progress submissions with the CNSC. However, several vendors intend on progressing with Vendor Design Review (VDR) in the next 1-5 years.

The evaluation identified that client engagement status and stakeholder engagement status were non-differentiators when considering the current state of vendor readiness. All vendors are currently in the process of having discussions with customers and stakeholders, and are further developing plans to advance in these areas.

8.3 Financial

The financial analysis is performed using the LCOE calculator and the initial data developed during the course of this study. The results are presented in detail in the following sub-sections.

8.3.1 SMR Deployment Target Levelized Cost of Electricity

The LCOE target costs are established by the incumbent technology option, namely, diesel. An SMR is deemed to be financially viable if its LCOE is competitive against the incumbent technology. Various sources report different numbers for diesel electricity costs in remote mines in Ontario. In order to compare SMR options to the diesel option on the same analysis

basis, diesel LCOE values are independently assessed in this study. The finalized target values are shown in Table 8-1.

Table 8-1: Target LCOE for remote mines in Ontario

Option	LCOE	Source
Continued Diesel Generation	\$0.30 -0.35/kWh	Hatch LCOE Calculation ⁵⁰

The LCOE and composition of the diesel-based electricity at a 6% discount rate are shown in Figure 8-1. It can be seen that the costs are dominated by diesel fuel costs followed by non-fuel O&M costs.

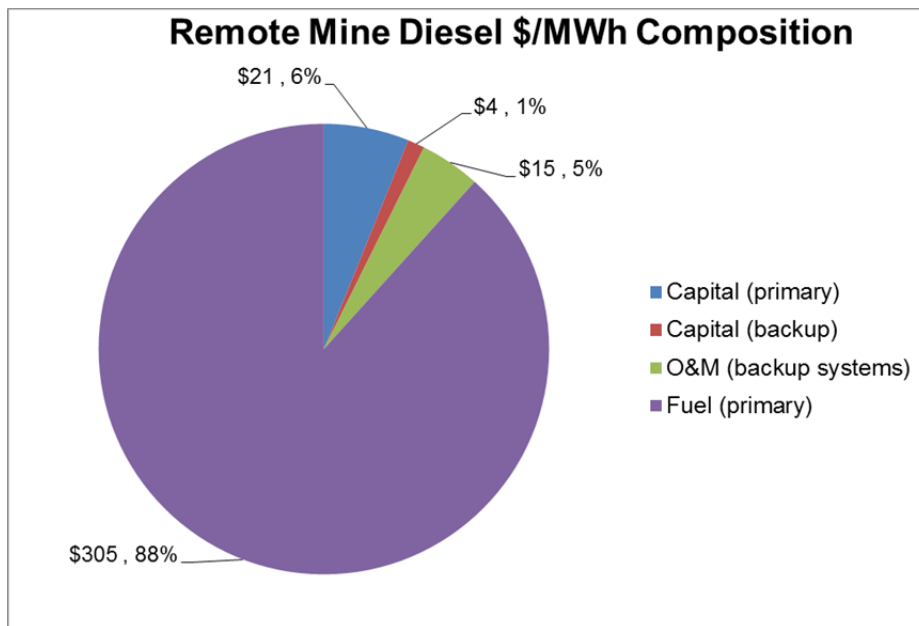


Figure 8-1: Levelized Cost of Electricity and the major cost components @ 6% Discount Rate

The preliminary LCOE of the nine SMR technologies ranges from \$193/MWh to \$288/MWh, depending on specific technology and specific mining site application. This represents estimated potential savings of up to \$152/MWh for SMR deployment for remote mines compared to current diesel power generation. The results show that all SMRs exhibited significant economic advantage over the diesel power option.

8.3.2 Discount Rate Sensitivity

Discount rate applied to future cash flows can drastically affect the perceived feasibility of a technology depending on how capital or ongoing cost-intensive a technology is. A general trend is that greater discount rates favour options that are less capital intensive and incur a

⁵⁰ The LCOE calculated for remote mine is consistent with the operating values reported in recent NI 43-101 reports for northern Canadian remote mines, such as Meadowbank mine (2015 report).

majority of their costs over time. Conversely, a lower discount rate will favour technologies that incur most costs up front or at the start of their life with less ongoing costs.

The results show that SMR economic assessments are favoured by low discount rates which are typical for capital intensive projects. On the other hand, diesel power generation economy is adversely impacted by low discount rates.

The majority of SMRs will remain competitive against diesel option between 0% and 10% discount rate assumptions.

8.3.3 LCOE Cost Components

The examination of the cost components reveals that the nuclear technology LCOE will be sensitive to capital costs, staffing, fuel costs, initial regulatory costs and carbon tax credits. The sensitivity of the LCOE calculation to these parameters and their impact on the economic competitiveness margin are examined in the next section.

Since diesel backup is assumed in the LCOE model, the technologies with lower capacity factors are penalized for consuming higher diesel fuel and receiving lower carbon tax credits. Additionally, the redundancy requirement in the model also penalizes the technologies with larger primary unit capacities.

9. Discussion

9.1 General

Hatch examined the deployment feasibility of very small nuclear reactors to replace diesel power in remote mines in Ontario. In this section, general commentary on the industry statutes and technologies are provided based on several observations made during the course of the study.

9.1.1 *Regulatory Aspects of SMRs*

While many SMR vendors indicated in their survey responses that they need to have regulatory certainty for the industry to move forward in Canada, Hatch found that the current Canadian regulatory system is adequate to meet very small nuclear reactor licensing needs.

While the initial regulatory cost is expected to be significant in micro-SMR economics, many reactors examined in this study can withstand over \$150 million in licensing costs without losing their economic competitiveness against the diesel power option, as long as the vendors can meet other cost targets. It should be emphasized that the vendors' costs covering R&D necessary to meet the regulatory requirements is not the regulatory cost. Many vendors often use these two different types of costs interchangeably. Any millions of dollars that vendors have to spend to prove their design safety represent the technology development cost. The regulatory licensing costs are the CNSC's service fee to examine the application, as well as the environmental assessment and public engagement costs.

In addition, the CNSC utilizes the concept of precedent-based licensing. When a licensee is successful in licensing one facility and a subsequent application is filed for another site based on the same technology, then the regulator only examines the differences between the existing licensing case and the new one. Such a practice will reduce the technology-related portion of the licensing cost for subsequent units. Thus, the licensing cost is expected to decrease for nth-of-a-kind units.

The final commentary on the regulatory aspect of SMRs is that any technologies that are based on novel concepts will have higher initial R&D cost burdens to meet the regulatory requirement.

9.1.2 *Vendor Observations*

Hatch observed the vendors throughout a series of interactions and took note of their corporate professionalism, competences as nuclear vendors, and willingness to explore and engage Canadian market participants. The ways in which vendors responded to the survey requests and how they provided the responses were important factors in the evaluation, in addition to the actual contents in the responses.

9.2 Social Economic Impact

Although a social impact study is not within the scope of this study, the impact is estimated at an indicative level to examine the needs for further analysis. The methodology and SMR

economic multipliers are directly taken from a U.S. study⁵¹ without any independent examination of their accuracy.

9.2.1 Methodology

The economic impact of an SMR is calculated from estimated expenditures for the manufacturing and construction of each unit and the annual revenues derived from the sale of electricity from each unit. The expenditures are further divided into manufacturing and construction categories. The U.S. study reports that the economic impact multipliers and employment factors in Table 9-1 are appropriate for SMR economics.

Table 9-1: SMR economic impact multipliers

	Direct Impact	Value Added (% of direct impact)	Earning (% of direct impact)	Employment (persons per \$1 million)
Manufacturing	unit installed cost × 0.87 (manufacturing) × 2.6	47.8%	30.28%	5.03
Construction	unit installed cost × 0.13 × 2.67	49.7%	35.78%	7.12
Revenue	Annual electricity revenue × 1.81	63.77%	25.89%	3.49

Since a Canadian nuclear supply chain is not currently positioned to produce the exotic types of low-enriched fuel that all the SMR technologies are proposing to use, it is assumed that the Ontario share in an SMR manufacturing process would be limited to 50%. Further, it is assumed that Ontario will retain 100% of the construction and operation-related economic impact for SMR units deployed in the province, but 0% for units deployed in other jurisdictions. Ontario's share of the SMR industry participation is assumed as shown in Table 9-2.

⁵¹ David Solan et al., 'Economic and Employment Impacts of Small Modular Nuclear Reactors', The Energy Policy Institute, Center for Advanced Energy Studies, June 2010.

Table 9-2: Ontario's share of economic participation based on SMR deployment location

	Ontario	Canada excluding Ontario	International
Manufacturing	50%	50%	50%
Construction	100%	0%	0%
Operation	100%	0%	0%

9.2.2 Potential Market Sizes

9.2.2.1 Ontario Remote Mines

The potential Ontario SMR deployment market is estimated to be about 22 MWe for Ring of Fire mines, as discussed in previous sections of this report. It is assumed that 50% of this market is addressable with SMR technology.

9.2.2.2 International Island Communities

The Small Island Developing States, or SIDS⁵², include 52 countries spanning the Caribbean, Atlantic, Indian and Pacific Oceans, as well as the South China and Mediterranean Seas. They range from low-income countries such as Haiti to high-income countries like Barbados and Singapore. Being small, often remotely-located, and usually without domestic fossil fuel reserves, these countries rely on expensive and volatile imported petroleum fuels for power generation. Often electricity generation consumes more than 10 percent of the total GDP in these countries as power is produced with diesel generators using this expensive imported fuel at over \$4/litre. In some cases, the electricity production cost exceeds 30 percent of the national GDP.

Including islanded communities in non-island state countries (i.e., coastal islands in Canada), there are more than several hundred communities⁵³ that heavily rely on diesel generation.

Many of these island communities are adopting renewable power technologies to reduce power cost. However, renewable technologies often lack the ability to be base load power supplies due to their intermittency, although they are able to reduce the diesel fuel consumption. Small nuclear reactors deployed as base load power sources can reduce the electricity cost substantially while improving the power quality in the system.

According to available U.S. Energy Information Administration data, the island states produced more than 80 billion kilowatt-hours in 2010. This is equivalent to 9.1 GWe of annualized generating capacity, a large portion of which can be economically replaced by small nuclear reactors. If it can be assumed that 10% of this market can be served by nuclear power, this represents approximately 910 MWe of generating capacity.

⁵² SIDS Action Platform, <http://www.sidsnet.org>, last accessed on January 29, 2016.

⁵³ <http://islands.unep.ch/>, last accessed on January 29, 2016.

9.2.2.3 Remote mines

The annual global energy use in the industrial sector is currently estimated as 6.45×10^{13} kWh/year⁵⁴. Although the mining share of energy consumption in the total industrial energy use differs from a country to another, it is estimated that 2% of the industrial energy use occur in the metals mining sector (excluding oil and gas extraction, coal mining, and metal smelting and refining)⁵⁵. Then, roughly a third of the mining energy is in the form of onsite electricity. Thus, the electricity consumption at existing mines currently represents 54.0 GW annualized load, assuming 2% industrial energy is consumed in metals mining and power generation operates at 90% capacity factor.

It is expected that many of these mines already have access to low-cost power sources such as hydro, which make the project profitable (i.e., if the power cost was prohibitively high, then the mine project would not have started in the first place). Small nuclear reactors would benefit only a fraction of the existing mines where high diesel-powered energy costs are impacting profitability; however, this still represents a significant market potential. If 5 percent of mines are in remote areas and they can be economically served by nuclear power, this market represents 2.70 GWe of generating capacity.

9.2.2.4 Potential Market Size Summary

The potential domestic and international micro-SMR deployment market is summarized in Table 9-3.

Table 9-3: Potential SMR service market size

Market segment	Ontario mines	International Island Communities	Remote mines
Total primary generating capacity	22 MWe	9.1 GWe	54 GWe
SMR deployment potential conjecture	11 MWe	910 MWe	2.70 GWe

9.2.3 Potential Economic Impacts

The potential economic impacts to Ontario were estimated by applying the average SMR installed cost of \$9,900/kWe used in this study to the U.S. SMR economic impact assessment methodology. In addition \$0.30/kWh is assumed for electricity sales in mining markets. The estimate further assumes that 100% of the target market is captured by an Ontario-based company. The results are shown in Table 9-4.

Table 9-4: Potential Economic Impact to Ontario Based on 100% Target Market Capture by an Ontario-based SMR Company

⁵⁴ International Energy Outlook 2013, U.S. Energy Information Administration, http://www.eia.gov/forecasts/ieo/ieo_tables.cfm

⁵⁵ Energy Use and Related Data: Canadian Mining and Metal Smelting and Refining Industries, 1990 to 2011, Canadian Industrial Energy End-use Data and Analysis Centre, March 2013.

Deployment Markets	Direct Impact (in \$ million)	Value Added (in \$ million)	Earnings (in \$ million)	Total (in \$ million)	Employment (person-years)
Ontario Mines	304	150	94	547	2,838
International Island Communities	20,378	9,741	6,171	36,290	182,538
Remote Mines (Global)	60,463	28,901	18,308	107,672	541,595

9.3 GHG Impact

As evident below, assuming an all-diesel generating facility for remote mining sites would result in inclusion in the proposed Ontario cap-and-trade program. It is important to note that only the energy generation at the mining site is being evaluated for carbon credits. The emissions arising from the mining operations themselves have been assumed excluded from scope. As a result, free allowances have not been considered in the analysis.

As per Hatch internal data, a diesel intensity factor of 2.79 kg CO₂e/L diesel was used. Due to the technological limit on improving diesel engine efficiency (i.e., continual technological innovations cannot reduce emissions at a constant rate indefinitely), this diesel intensity factor was held constant throughout the proposed mine lifetime.

9.3.1 Remote Mines

The GHG impact has been determined under two different energy demand scenarios for remote mines. The first is the reference scenario used throughout this study, which assumes a peak load of 22.05 MW corresponding to only the energy requirements of the Eagle's Nest mine. The second is a 68 MW high scenario, corresponding to multiple operating mines in the Ring of Fire region.

9.3.1.1 Reference Scenario

Under the reference scenario, an all-diesel generating facility would achieve an annualized average energy consumption of around 193,158 MWh. Over an assumed 20-year mine lifetime, this would correspond to a total of over 962 million litres of diesel consumed and subsequently almost 2.7 million tonnes of CO₂e emitted. Eliminating 2.7 million tonnes of CO₂e emissions is equivalent to removing approximately 28,500 passenger vehicles for 20 years⁵⁶.

A nuclear installation operating at a 100% capacity factor under the reference scenario remote mine in place of the all-diesel facility, accounting for only the escalating auction reserve price and ignoring strategic reserves and other costs associated with the cap-and-

⁵⁶ US EPA Greenhouse Gas Equivalency Calculator - <https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator>

trade program, would achieve around \$153 million in avoided carbon costs over the 20-year mine lifetime.

9.3.1.2 *High Scenario*

Under the high scenario, an all-diesel generating facility would achieve an annualized average energy consumption of around 595,680 MWh. Over an assumed 20-year mine lifetime, this would correspond to a total of almost 3 billion litres of diesel consumed and subsequently almost 8.3 million tonnes of CO₂e emitted, equal to 87,500 passenger vehicles driven for 20 years.

A nuclear installation operating at a 100% capacity factor under the high scenario remote mine in place of the all-diesel facility, accounting for only the escalating auction reserve price and ignoring strategic reserves and other costs associated with the cap-and-trade program, would achieve around \$477 million in avoided carbon costs over the 20-year mine lifetime.

9.4 **SMR Deployment Challenges and Recommendations**

In the SMR Vendor Survey, each vendor was provided an opportunity to describe the challenges they face in developing and deploying their technology in Canada. Further, the vendors were also asked to provide recommendations on how the government could assist in alleviating the challenges.

Based on conversations with the vendors and a review of the SMR business potentials, Hatch has also identified several challenges in the development and potential deployment of SMRs in Ontario. These challenges and the recommendations to alleviate them are described in the following subsections.

9.4.1 **Challenges**

- For any SMR technology to become commercially viable in Ontario, the following challenges need to be addressed:
- **Cost-effective demonstration sites availability:** While it is not mandatory to demonstrate an SMR technology before the design can be used for a commercial application, most vendors will need to demonstrate the technology before they can secure customers. Considering that the majority of the licensing cost is associated with the environmental assessment and public engagement activities, it is highly cost-effective to place a demonstration SMR unit at an existing nuclear site. The SMR industry generally recognize that Canadian Nuclear Laboratories at Chalk River, Ontario Power Generation's Pickering and Darlington sites, the Bruce Power site and Fedoruk Centre in Saskatchewan are potential demonstration sites for emerging SMR units. However, not all of these sites are available for SMR demonstrations due to the risk of impacting the existing site safety cases.
- **Qualified operators:** An SMR technology vendor can establish themselves as a nuclear operator or they will need to secure a qualified nuclear operator who will become the

licensee for the facility. In the latter case, there are a limited number of companies in Ontario that can support SMR vendors, namely OPG, Bruce Power and CNL to some extent.

- Limited market potential: Micro-SMRs are niche market products, and there are limited numbers of sites in Canada where the technology will be commercially viable. On the other hand, the revenue per site is limited due to the small unit sizes whereby vendors will need to deploy multiple units before they can recover the initial technology development costs. Due to the need for demonstration of the nuclear technologies, it is likely that the first-mover advantage will be significant in the micro-SMR industry. Thus, the number of SMR technologies that will be commercially successful will likely to be two or three at most.
- Demonstration unit financial return: While most of the SMRs studied in this report are competitive against diesel power generation in remote areas, the cost to produce power is substantially higher than the grid connected electricity prices. If an SMR demonstration unit is built at a grid-connected location, the electricity revenue from the unit will not be adequate to cover the reactor

9.4.2 Recommendations

- In order to alleviate the challenges identified above and to attract SMR vendors to come to Ontario for technology development and manufacturing activities, Hatch recommends that the following approaches are considered by the Ontario Ministry of Energy.
- Involvement with technology selection to support operator engagement and demonstration site provision: As discussed earlier, the micro-SMR market in Canada will likely be serviced by a small number of vendors who were the first to reach commercialization. Not all vendors who are in the race will bring equal benefits to Ontario's economy; thus, the government should aim to identify and support the vendors who will bring the most benefit to the province. The government will be able to leverage the fact that the prime technology demonstration sites are located in Ontario and that two strong candidate operators are Ontario companies.
- Demonstration of continued government interest in the industry: A few countries are now showing signs of strong interest in micro-SMR development, or openly supporting their domestic development programs with public funding. These countries include the United States, the United Kingdom and Russia. In order to attract the technology developers to conduct their business activities based in Ontario, it is critical that the government shows continued interest in this budding industry. Hatch believes that there are several cost-effective ways to publicly demonstrate the government interest, including:
 - ◆ Publicly announced SMR studies and investigations (further discussed in the next section)

- ◆ Small grants for the SMR industry to develop Ontario's nuclear supply chain integration plan
- ◆ Inclusion of SMR technologies in clean power technology discussions.
- Provision of stop gap funding for the demonstration units: The previous section discussed the financial challenges involved with demonstration units at a grid-connected location. The potential funding provision could include a feed-in tariff (FIT) program and a loan-guarantee, or a public-private partnership (PPP). In case of the FIT, the cost will be capped by the small amount of power that these units can produce (e.g., maximum two units with 5 to 10 MWe capacity). For a loan-guarantee or a PPP arrangement, the cost of the demonstration unit will have to be recovered from future commercial unit sales.

9.5 Future Works and Path Forward

Hatch recommends that a few follow-up studies are performed by the Ministry of Energy to allow the Ontario government to make well-informed decisions to determine if, when, and how they may participate in the development of the micro-SMR industry. In addition, the reference and the accelerated timelines for SMR deployment are provided to indicate when government actions may be necessary.

9.5.1 Refinement of the Current Study

This feasibility study has a few limitations as the first-of-a-kind study to evaluate micro-SMR deployment in remote mines. In order to improve the study results, Hatch recommends that the following refinements are performed:

- Databank update: The databank input values used in this study need to be updated with more accurate vendor information. It is recommended that the Ministry enters into confidentiality agreements with select vendors for the solicitation of more detailed information.
- Initial technology development effort and first-of-a-kind unit cost estimates: The cost and effort to develop the first licensable unit is expected to be significant for certain SMRs, especially those that ranked low in terms of technology and vendor readiness levels in this report. These parameters need to be investigated to accurately determine the technology deployment timeline.
- Site specific case studies: Once a specific SMR design is selected for further evaluation, the technology and a site-specific economic evaluation should be performed, as the current financial model is based on the average characteristics of aggregated sites which may favour certain technologies over others.

9.5.2 Technology Selection Studies

In order to determine which SMR technology will be most beneficial to Ontario, detailed socio-economic impact analyses will be required. Although high-level estimates for socio-economic impacts are provided in this report, the uncertainties in the findings are not quantified. In order

to rectify this deficiency in the findings, the following studies are recommended prior to soliciting vendors' business cases:

- Methodology verification: the methodology to estimate the socio-economic impacts in the US SMR economic impact report⁵¹ needs to be verified for an Ontario application.
- Market study: the potential market size for micro-SMRs needs to be examined in further detail to determine the potential economic impacts to the manufacturing sector in Ontario.
- Ontario manufacturing study: the current status of the nuclear supply chain in Ontario and its potential participation in the SMR industry development must be quantified.

9.5.3 **Timelines**

Figure 9-1 shows the reference timeline for the deployment of SMRs in Canada, based on the assumption that a vendor will go through the CNSC's pre-licensing vendor design review (VDR) processes prior to submitting a demonstration site licensing application. The timeline is created based on the current understanding of the SMR industry development in Canada. The flags above the timeline are potential vendor activities and the flags below the timeline are proposed government actions to maximize the influence on the industry.

Prior to announcement of a potential program, necessary key government actions may include engagement with the Ministry of Northern Development and Mines and the nuclear operators in Ontario in regards to potential SMR deployment. An additional necessary action may include wider discussion with the federal government, its agencies, and nuclear industry partners regarding a potential pilot project site, a business model (P3), economic development, nuclear innovation and research at universities, supply chain development, and the level of government support required.

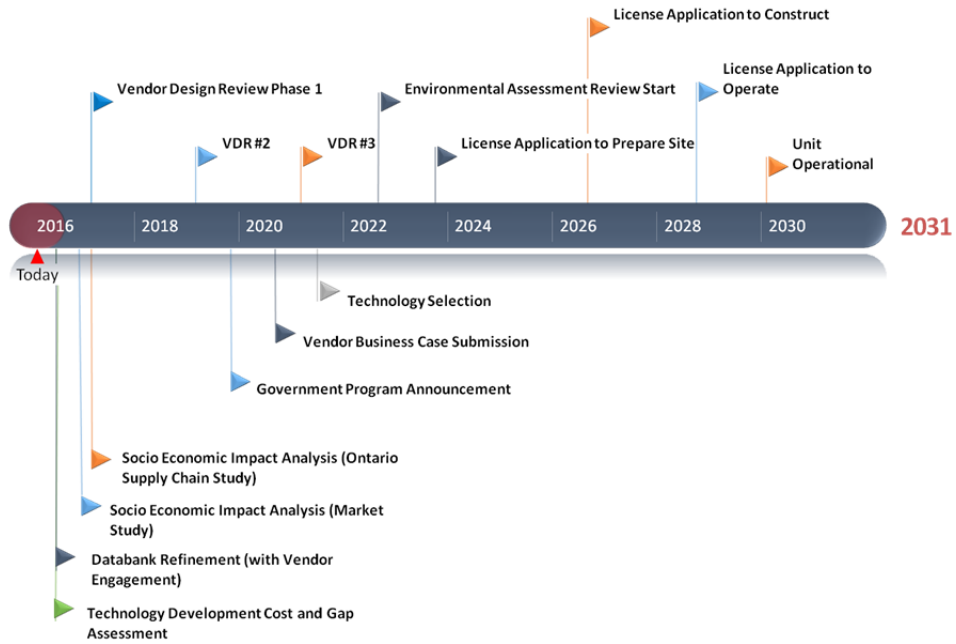


Figure 9-1 Reference SMR Deployment Timeline and Timing of Potential Ontario Programs

Figure 9-2 shows the accelerated timeline for SMR deployment in Canada. This timeline assumes that a vendor with a relatively mature technology may skip the pre-licensing review and go directly for a commercial site licensing application. In this case, the vendor will take higher licensing risk but, if successful, the first-mover will have a significant advantage in securing the future market shares. On the other hand, the government opportunity to exert any influence on technology selection and supply chain will be reduced unless fast actions are taken. Hatch believes that the accelerated timeline for SMR deployment is less likely than the reference timeline.



Figure 9-2 Accelerated SMR Deployment Timeline and Timing of Potential Ontario Programs

10. Conclusion

In order to assist the Ontario Ministry of Energy in properly assessing the benefits and risks associated with deployment of SMRs to replace the incumbent diesel power generation technology and remote mines in Ontario, a multi-dimensional deployment feasibility study of SMRs is conducted by Hatch. More specifically, the technology compatibility with the site requirements, lifetime economic performances, technology maturity, and vendor readiness levels are examined.

Although a few SMR feasibility studies have been produced by the United States and the United Kingdom on utility-scale water-cooled SMRs, an attempt to assess micro-SMRs in niche market applications has not been previously made. Thus, this study first adapts Hatch's in-house developed evaluation methodology and tools to the specific scope and requirements of SMR applications in northern Ontario, in addition to creating a databank to collect relevant technical and financial information to be used as the reference input values.

The entries into the databank are collected from public and Hatch internal sources, as well as from SMR technology vendors via surveys.

10.1 Major Findings

After initially examining ninety SMR technologies currently in development, initial screening filters are applied to shortlist nine technologies for detailed assessment in remote mine deployment scenarios.

The technology compatibility evaluation result shows high compatibility levels for the majority of designs for their remote applications, with the exception of one design that is primarily being developed for on-grid application. This result indicates that the technology vendors reflected the site characteristics and conditions in developing the SMR design requirements.

Most SMRs are in medium levels of technology readiness based on the technology maturity evaluation results. The majority of technologies score between 4 and 7 in the TRL scales with only one technology scoring below 3 on average, where 1 means that basic principles are observed and 9 means that the technology is commercially available. The technology maturity qualitatively indicates what future R&D and development costs associated with the technology will be necessary before the technology can reach a licensable stage.

Technologies with lower scores will incur additional development expenses than those with higher scores.

The vendor readiness evaluation shows that there are two different groups in the micro-SMR development industry; a group of established nuclear technology companies with technical and financial resources but with a fragmented interest in the micro-SMR market, and a group of venture companies that lack resources but have a focused interest in the market. Both groups scored poorly in terms of regulatory approval, client engagement, and stakeholder

engagement, indicating that the SMR industry in Canada is still in a very early development stage.

Finally, the economic competitiveness analysis shows that all SMRs are competitive against diesel power generation technology. In remote mine scenarios at a 6% discount rate, potential savings of up to \$152/MWh are estimated. While the SMR economic competitiveness is only indicative because of many uncertainties in SMR input costs, the gap between diesel and SMR LCOE in combination with conservative cost values used in this study indicates that there is a healthy margin of error in the economic competitiveness result.

In addition to performing an analysis on remote mining applications of SMRs for the Ontario Ministry of Energy, Hatch also examined the applicability of this study on assessment of SMR deployment in remote communities in northern Canada for the Natural Resources Canada (NRCan).⁵⁷

While the key findings above for technology and vendor readiness of SMR designs for Ontario remote mines are applicable to Canada's northern remote mines and communities to a large extent, the key differences are as follows:

- Four SMR designs under 5 MWe out of the nine shortlisted SMRs are identified as potentially suitable designs for specific characteristics of remote communities such as redundancy and reliability configurations, load following capability, and expected load growth.
- Three of the four SMRs for potential deployment in remote communities are expected to be economically competitive against the incumbent diesel energy source with potential power cost-savings up to \$187/MWh.

10.2 Potential SMR Benefits

The study also examines the potential benefits of SMRs to the provincial environment and economy. The economic assessment shows that micro-SMRs will be competitive against diesel power generation technology in mining power applications. Since remote mines produce their own power, the potential benefit of SMRs to the province is mainly the reduction of greenhouse gas emissions. In the reference 22 MW power demand scenario for Ring of Fire mining, 962 million liters of diesel consumption and 2.7 million tonnes of CO₂ equivalent GHG emission will be avoided during the 20-year project lifetime. In the high 68 MW demand scenario, almost 3 billion liters of diesel and 8.3 million tonnes of CO₂ equivalent GHG emission will be avoided during the project lifetime.

Finally, deployment of SMRs in remote Ontario mining sites will have direct and indirect impacts on Ontario's economy depending on the province's participation level within the

⁵⁷ For illustrative purposes, Hatch examined off-grid communities in Northern Ontario based on available data from the former Ontario Power Authority (OPA), Aboriginal Affairs and Northern Development Canada (AANDC), and NRCan.

nuclear industry in developing and manufacturing SMR technologies. Based on 50% participation in manufacturing of SMRs, the impacts are estimated to be approximately \$4 billion and 20,000 employment-years in the case where SMRs can be fully deployed to potential Canadian remote areas, with up to \$148 billion and 542,000 employment-years if SMRs can be exported to serve potential international remote communities and mines.

10.3 Technology Selection

The largest obstacle in SMR development and deployment in Canada is the availability of economical prototype demonstration sites. Since many of the micro-SMR designs are novel, a demonstration unit is likely to be required before commercial units can be deployed to a remote location. The commercial units in remote locations are economically competitive against the incumbent diesel power generation technology and they will not require subsidies. However, the demonstration units will have to be installed at grid connected locations where electricity costs will not provide adequate return for SMRs. Therefore, some vendors already identified the need for a feed-in-tariff program for their demonstration units. Another issue is that there are limited numbers of potential demonstration sites in Canada that can host an SMR unit without incurring significant siting and environmental assessment costs. If a current Class I nuclear facility can host an SMR unit on the same site, which will increase the total source term but only in a small quantity, then the technology demonstration cost can be reduced. These sites are namely Chalk River Laboratories, OPG's Pickering and Darlington sites, and the Bruce Power site.

In order to address this bottleneck, it may be necessary for the government to select a few technologies that will be supported for demonstration based on the potential benefit to the province as well as other evaluation criteria developed in this study with an updated databank.

Appendix A

Glossary and Abbreviations

Term	Definition
BWR	Boiling Water Reactor – A type of light water nuclear reactor.
CANDU	Canada Deuterium Uranium - a Canadian developed pressurized heavy water reactor (PHWR)
CNSC	Canadian Nuclear Safety Commission – an independent federal government agency that regulates the use of nuclear energy and material.
Economics (Financing)	Upfront capital cost related to an SMR project – The cost includes plant capital cost, waste management fund and regulatory licensing cost
Economics (Lifetime)	Total cost of an SMR project including operation, fuel, backup fuel and decommissioning costs.
GHG	Greenhouse Gas – a gas in the atmosphere that absorbs and emits radiation within the thermal infrared range.
HTGR	High Temperature Gas Reactor – a type of nuclear reactor that uses a gas as coolant
IAEA	International Atomic Energy Agency – an international organization that promotes the peaceful use of nuclear energy and to inhibit its use for any military purpose.
LCOE	Levelized Cost of Electricity – a measure of economic competitiveness of a power generating technology.
LWR	Light Water Reactor – a type of nuclear reactor that uses light water as a coolant.
MOX	Mixed Oxide – a type of nuclear that contains more than one oxide of fissile material, usually consisting of plutonium blended with natural uranium
MSR	Molten Salt Reactor – a type of nuclear reactor that uses a molten salt as coolant and/or the fuel.
NWMO	Nuclear Waste Management Organization – a Canadian not-for-profit organization responsible for designing and implementing Canada’s plan for safe long-term management of used nuclear fuel.
PHWR	Pressurized Heavy Water Reactor – a type of nuclear reactor that uses heavy water as a coolant.
SMR	Small Modular Reactor – a modular nuclear reactor typically 500 MWe or smaller.
TRISO	Tristructural-isotropic – a type of micro nuclear fuel particle.

TRL	Technology Readiness Level – a measure of a technologies readiness for operation
UOX	Uranium Oxide – a type of nuclear fuel, common in LWRs and PHWRs.
VDR	<p>Vendor Design Review – A pre-licensing vendor design review is an assessment of a nuclear power plant design based on a vendor's reactor technology. The assessment is completed by the CNSC, at the request of the vendor. The words “pre-licensing” signifies that a design review is undertaken prior to the submission of a licence application to the CNSC by an applicant seeking to build and operate a new nuclear power plant.</p> <p>This review does not certify a reactor design or involve the issuance of a licence under the <i>Nuclear Safety and Control Act</i>, and it is not required as part of the licensing process for a new nuclear power plant. The conclusions of any design review do not bind or otherwise influence decisions made by the Commission.</p> <p>The objective of a review is to verify, at a high level, the acceptability of a nuclear power plant design with respect to Canadian nuclear regulatory requirements and expectations, as well as Canadian codes and standards. These reviews also identify fundamental barriers to licensing a new design in Canada and assure that a resolution path exists for any design issues identified in the review.</p> <p>A vendor who has completed a phase 2 pre-licensing vendor design review, has committed to increased regulatory efficiencies at the time of licensing. The results of Phase 2 will be taken into account mainly for the Construction Licence Application and is likely to result in increased efficiencies of technical reviews.</p> <p>The reviews take place in three phases, each of which is conducted against related CNSC regulatory documents and Canadian codes & standards:</p> <p>Phase 1: Pre-Licensing Assessment of Compliance with Regulatory Requirements: This phase involves an overall assessment of the vendor's nuclear power plant design against the most recent CNSC design requirements for new nuclear power plants in Canada as indicated in REGDOC 2.5.2, Design Of Reactor Facilities: Nuclear Power Plants or Design of Small Reactor Facilities (RD-367) as applicable, as well as all other related CNSC regulatory documents and Canadian codes & standards.</p> <p>Phase 2: Pre-Licensing Assessment for Any Potential Fundamental Barriers to Licensing: This phase goes into further details with a focus on identifying any potential fundamental barriers to licensing the vendor's nuclear power plant design in Canada.</p> <p>Phase 3 Follow-up: This phase allows the vendor to follow-up on certain aspects</p>

of Phase 2 findings by:

- seeking more information from the CNSC about a Phase 2 topic; and/or
- asking the CNSC to review activities taken by the vendor towards the reactor's design readiness, following the completion of Phase 2.

VRL

Vendor Readiness Level – a measure of a vendors readiness to build and operate a nuclear reactor

Appendix B

Initial SMR List

Reactor Name	Developer	Type
ACPR50S	CGN, China	-
4S	Toshiba, Japan	MSR
ABV-6M	OKBM Afrikantov	integral PWR
ACP100	NPIC/CNNC, China	integral PWR
ACPR50S	CGN, China	PWR
ACPR100	CGN, China	PWR
Adams Engine	Adams Atomic Engines	HTR
AHWR	Babha Atomic Research Center (BARC)	PHWR
ALLEGRO	European Partners	GCFR
ANGSTREM	OKB Hidropress	LMR
ANTARES	AREVA	HTR
ARC-100	Advanced Reactor Concepts	LMFR
BREST	RDIFE, Russia	FNR
CAP150	SNERDI, China	PWR
CAREM	CNEA & INVAP, Argentina	integral PWR
CAWB	Copenhagen Atomics	MSR
CEFR	CNEIC	liquid metal cooled fast reactor
CNP-300	CNNC, operational in Pakistan & China	PWR
DMS	Hitachi-GE	BWR
EGP-6	at Bilibino, Siberia (cogen)	LWGR
ELENA	RRC KI, Russia	direct conversion water-cooled
Elysium	Elysium Industries, USA	MSR
EM2	General Atomics (USA)	HTR, FNR
ENHS	University of California (Berkeley)	LMFR
FBNR	Federal University of Rio Grande do Sul	Fixed Bed
FHR	Massachusetts Institute of Technology	MSR
Flexblue	DCNS, France	Water-cooled SMR
Fuji MSR	International Thorium Energy & Molten Salt Technology Inc. Company (IThEMS)	LMR
GEMSTAR	Virginia Tech and ADNA Corp.	LMFR
Gen4 module (Hyperion)	Gen4 (Hyperion), USA	FNR
GFP HTGR	GFP, USNC, Hyundai(?)	HTGR
GTHTR	Japan Atomic Energy Agency (JAEA)	HTR

Reactor Name	Developer	Type
GT-MHR	OKBM Afrikantov	HTGR
HTR-PM	Institute of Nuclear Energy and New Technology (INET) at Tsinghua University & Huaneng Shandong Shidaowan Nuclear Power Company (HSSNPC)	HTR
Hybrid	Hybrid Power Technologies	HTGR Variant
IMR	Mitsubishi heavy Ind, Japan	integral PWR
Integral MSR	Terrestrial Energy, Canada	MSR
IRIS	International Consortium	PWR
KLT-40S	OKBM, Russia	PWR
LeadCold	LeadCold, Sweden/Canada	lead-cooled
Leadir-PS100	Northern Nuclear, Canada	lead-cooled
L-ESSTAR	LakeChime	LMFR
LFTR	Flibe Energy	MSR
LSPR	Tokyo Institute of Technology	LMR
MARS	Kurchatov Institute	LMR
MHR-100	OKBM Afrikantov	modular helium reactor
Molten Chloride Fast Reactor	Southern Company Services	Fast reactor
Moltex	Moltex Energy	MSR
mPower	Babcock & Wilcox + Bechtel, USA*	integral PWR
MRX	Japan Atomic Energy Research Institute (JAERI) - Mitsubishi Heavy Industries (MHI)	PWR
MTSPNR (GREM)	N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET)	HTR
NHR-200	NHR-200	integral PWR (heating)
NIKA-70	N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET)	PWR
NP-300	Technicatome (AREVA)	PWR
NuScale	NuScale Power + Fluor, USA	integral PWR
PB-FHR	UC Berkeley, USA	MSR
PBMR	PBMR, South Africa; NPMC, USA*	HTR
PEACER	Nuclear Transmutation Energy Research Centre of Korea (NUTRECK)	LMR
PHWR-220	NPCIL, India	PHWR
Prism	GE-Hitachi, USA	FNR
RADIX	Radix Power, USA	integral PWR
RADIX Power	Radix Power and Energy Corporation, USA	IPWR
RAPID	Central Research Institute of Electric Power Industry (CRIEPI), Japan	LMR

Reactor Name	Developer	Type
RITM-200	OKBM Afrikantov	integral PWR
RUTA-70	RDIPE, Russia	integral pool-type heating reactor
SAKHA-92	OKBM Afrikantov	PWR
SC-HTGR (Antares)	AREVA	HTR
SHELF	RDIPE, Russia	PWR
SMART	KAERI, South Korea	integral PWR
SMART (UNITHERM)	Dunedin	Nuclear Battery
SmATHR	Oak Ridge National Laboratory	MSR
SMR-160 (HI-SMUR)	Holtec	PWR
STAR	Argonne National Laboratories	LMFR
Starcore HTGR	StarCore, Canada	HTGR
STL	Steenkampskraal Thorium Limited, South Africa	PBMR
SVBR-100	AKME-engineering, Russia	FNR
TAP	Transatomic	MSR
Thorcon MSR	Martingale, USA	MSR
Thorenco	Thorenco	LMFR
TMSR-SF	SINAP, China	MSR
TPS	General Atomics (USA)	PWR
U-Battery	Urenco	HTGR
UNITHERM	NIKIET, Russia	PWR
UPower	U-Power Technologies, MIT, USA	-
VBER-300	OKBM, Russia	PWR
VK-300	RDIPE, Russia	BWR
VKT-12	OKB Hidropress	BWR
VVER-300	OKB Hidropress	-
Westinghouse SMR	Westinghouse, USA*	integral PWR
Xe-100	X-energy, USA	HTR