Feasibility Study of Small Modular Reactors in the Yukon

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EXECUTIVE SUMMARY

The negative impacts of climate change are being felt globally, including in the Yukon which has experienced thawing permafrost, weather changes, more frequent extreme weather events, more severe forest fires, melting of glaciers, and more. The Yukon has declared a climate emergency and committed to a 10-year renewable electricity plan to help reduce greenhouse gas (GHG) emissions. The Yukon's goal is to reduce GHG emissions to 45% of 2010 levels by 2030. Yukon 2020 emissions modeling suggests that the existing commitments along with federal policies and programs, are expected to reduce 2030 GHG emissions by approximately two-thirds of the 45 percent target. Additional measures are therefore needed to achieve the Yukon emissions reduction target.

Although Small Modular Reactors (SMRs) were not included in the Yukon's climate strategy, they are being investigated by the Government of Yukon as a means of providing continuous power to the Yukon's communities. This feasibility study assesses the role and benefits SMRs could provide in the Yukon for three different use cases: the Yukon grid, off-grid mine sites, and microgrid communities. For each of these use cases, SMRs with an electrical output of 100 MWe, 25-30 MWe, and <5 MWe are considered respectively. Canadian SMR deployment projects with similar electrical generation capacities are used as examples in each case. The assessment criteria used to study SMR feasibility in the Yukon included technology and infrastructure availability, logistical considerations, fuel availability and management, benefits, cost and competitiveness, regulatory readiness, and public perception.

The analysis of technology and infrastructure availability focuses on current SMR projects that are underway in Canada. Within the next 12 years or so, it is expected that SMR's will be deployed and commercially operating in Saskatchewan, New Brunswick, and Ontario, with the first SMR expected to be operating by 2027. It is expected that if the Yukon were to pursue SMR deployment, current projects will have progressed and a Canadian supply chain will be forming. The availability of technology does not pose a barrier for SMR deployment in the Yukon, but it is recommended to allow current Canadian projects to progress in order to provide experience to inform future potential SMR deployment in the Yukon.

Logistical considerations are assessed, such as staffing requirements, transportation, and refueling cycles. Although staffing requirements are much less for SMRs compared to traditional nuclear plants, specialized staff such as nuclear operators will need to be trained or relocated to the Yukon since there is currently no nuclear industry in the territory. Currently, all potential sites for SMR deployment will need to be accessible by road for SMR deployment to be feasible. The refueling cycles for the SMRs used as examples for the use cases ranged from 3 to 20 years, greatly reducing the need for the transportation of fuel as compared to existing fossil fuel energy infrastructure.

The availability of fuel for SMR designs is assessed, specifically the commonly used High Assay Low Enriched Uranium Fuel (HALEU). Currently, there is no domestic supply chain for this fuel, in

which it has historically been imported from Russia. SMR vendors and the governments of Canada and the United States are working to create a domestic supply chain. Given ongoing efforts to improve the domestic fuel supply chain, availability of fuel is not expected to be a barrier based on the timelines expected for the Yukon. The Nuclear Waste Management Organization (NWMO) is responsible for the transportation and long-term storage of nuclear waste in a deep geological repository in the province of Ontario.

Various benefits from SMR deployment in the Yukon are identified. Benefits include carbon free energy generation, reduction of GHG emissions, minimal land use compared to other energy options, local economic development and positive impacts on GDP and revenues, reliable and consistent energy production regardless of external factors, and the production of heat that can be used for district heating and industrial applications.

SMRs could be economically competitive with other energy options. The initial analysis shows that SMRs have a lower Levelized Cost of Electricity (LCOE) than comparable systems of diesel, wind and diesel, solar and diesel, wind and battery, solar and battery, hydro, and liquified natural gas. The overnight capital costs for SMRs are higher initially, with lower fuel costs over time.

In terms of regulatory readiness, there are no major impediments to the licensing of SMRs for deployment in the Yukon. However, the Yukon Environmental and Socio-Economic Assessment Board (YESAB) has never undertaken a nuclear assessment process and is expected to require additional support and personnel to undertake the assessment of a nuclear project.

The public perception of nuclear energy in the Yukon presents some challenges, but it would not be an insurmountable barrier. Many concerns with nuclear energy repeated by respondents to the engagement study in the Yukon were addressed in this feasibility study. Most of the current energy issues in the Yukon that were identified could be solved with the implementation of SMRs. Although 22 of the 23 respondents were characterized as supportive of nuclear power, this is likely not representative of the general population, since only 3 respondents had little to no knowledge on nuclear power and all respondents were knowledgeable on energy systems broadly. As a result, participants in the engagement study had the perception that Yukoners may be biased against nuclear energy and that was noted as a challenge. Concerns related to bias against nuclear energy need to be addressed through further education and outreach activities.

This feasibility study shows that the future deployment of SMRs in the Yukon is feasible and there are no major barriers to their eventual deployment. For economic feasibility, there are requirements for a higher up-front investment and deployment situations allowing high-capacity factor to make economical use of the energy SMRs provide. Based on currently anticipated capacity needs and planned projects, remote communities, and off-grid mine sites appear to be the most optimal use cases for GHG reductions, although this could change in the future. It is recommended to allow further advancement of current SMR projects in Canada before considering deployment of SMRs in the Yukon. It is also recommended to consult with YESAB well in advance of any potential SMR development, given the lack of regulatory experience with SMR projects. Additional engagement to determine public perception of SMRs across a broader population is recommended, given that the individuals included in outreach to date were knowledgeable on energy systems and may not be representative of the general population.

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1. INTRODUCTION

1.1 Background

The impacts of climate change are already being felt in the Yukon. Northern Canada has seen a 2.3 °C increase in average temperature since 1948 with the most rapid rise in temperature occurring in the Yukon and Northwest Territories [1]. The Government of Yukon as well as many Yukon communities and First Nations governments have declared a climate emergency. Climate change poses a threat to the culture and way of life of First Nations people and the Yukon will continue to experience climate change impacts including thawing permafrost, weather changes, more frequent extreme weather events, more severe forest fires, melting of glaciers, and more.

To fight climate change, in December 2015, Canada signed the Paris Agreement and committed to cutting Greenhouse Gas (GHG) emissions to limit the global average temperature rise to well below 2 °C as well as pursue efforts to limit the increase to 1.5 °C [2]. Under Canada's 2030 Emission Reduction Plan [3], Canada strengthened this commitment and set an emission reduction target of 40 to 45 percent below 2005 levels by 2030 and achieving net-zero emissions by 2050.

In 2020, the Government of Yukon published the Yukon's climate strategy, *Our Clean Future: A Yukon strategy for climate change, energy, and a green economy* [1]. The strategy sets four goals to achieve a clean future including: reducing the Yukon's GHG emissions; ensuring Yukoners have access to reliable, affordable, and renewable energy; adapting to the impacts of climate change; and building a green economy. The strategy focuses on the 10-year period prior to 2030 to begin urgently taking steps towards achieving the Yukon's goals and to hold the Territory accountable. The Government of Yukon set an emission reduction target of 30 percent lower than 2010 levels by 2030 for transportation, heating, electrical generation, commercial and industrial activities, waste, and other areas. In 2021, the emission reduction target increased to 45 percent lower than 2010 levels by 2030 following a territorial election [4].

Small Modular Reactors (SMRs) were not included in the Yukon's climate strategy but are a green generation option being investigated by the Government of Yukon as a means of providing continuous power to the Yukon grid, remote microgrid communities, and off-grid mine sites while simultaneously pursuing their emissions reduction targets. The Government of Canada's Fall Economic Statement for 2022 recognized SMRs as a clean energy technology and have included them in an investment tax credit up to 30% [5]. The Yukon signed on to Canada's SMR Action Plan and committed to "monitor the progress of SMR technologies throughout Canada with the goal of identifying potential for applicability in our northern jurisdiction" [6]. The Government of Yukon contracted Calian Nuclear to assess potential opportunities for the use of SMRs in the Yukon.

1.2 Objectives

The purpose of this document is to assess the potential opportunities and understand the emission reduction benefits for SMRs in the Yukon as well as identify potential barriers to adoption within the territory.

1.3 Scope

This study provides a high-level overview of SMR technologies and assesses the suitability of SMR technologies for three potential use cases in the Yukon including generation for the Yukon grid, remote off-grid mine sites, and microgrid communities. This study is limited to publicly available information on SMRs undergoing a pre-licensing vendor design review by the Canadian Nuclear Safety Commission (CNSC) and leverages the findings of previous assessments but does not recommend any specific SMR designs or vendors.

1.4 Acronyms

Acronym	Definition
BWR	Boiling Water Reactor
CO_2e	CO_2 Equivalent
CRF	Capital Recovery Factor
CSNC	Canadian Nuclear Safety Commission
DNNP	Darlington New Nuclear Project
DSM	Demand Side Management
ERAP	Emergency Response Assistance Plan
FCM	Fully Ceramic Micro-encapsulated
GFP	Global First Power
GHG	Greenhouse Gas
HALEU	High-Assay Low-Enriched Uranium
HTGR	High Temperature Gas Reactor
IAA	Impact Assessment Act
IPP	Independent Power Production
Kt	Kilotonnes
LCOE	Levelized Cost of Electricity
LFR	Lead-Cooled Fast Reactor
LNG	Liquified Natural Gas
LoM	Life of Mine

MLESP	Mayo Enhanced Storage Project
MMR	Micro Modular Reactor
MSR	Molten Salt Reactor
NB	New Brunswick
NFWA	Nuclear Fuel Waste Act
NRCan	Natural Resources Canada
NWMO	Nuclear Waste Management Organization
O&M	Operations & Maintenance
OPG	Ontario Power Generation
PWR	Pressurized Water Reactor
SFR	Sodium-Cooled Fast Reactor
SLESP	Southern Lakes Enhanced Storage Project
SMR	Small Modular Reactor
SOP	Standing Offer Program
TDG	Transportation of Dangerous Goods
USNC	Ultra Safe Nuclear Corporation
U-235	Uranium-235
VDR	Vendor Design Review
YEC	Yukon Energy Corporation
YG	Yukon Government
YIS	Yukon Integrated System

2. METHODOLOGY

2.1 Approach

This section summarizes the approach employed to assess the potential opportunities for SMR deployment in the Yukon and the potential benefits and barriers. The approach consists of three steps as follows:

1. **SMR Technology Review:** The characteristics and design features of various SMRs under development are reviewed and summarized by the type of SMR technology. The SMR technologies assessed are selected from the vendor designs undergoing the CNSC pre-licensing vendor design review process [7]. The information summarized includes:

    - Type of SMR,
    - Electrical and thermal generation capacity (size),
    - Design features,
    - Load following and base load suitability, and
    - Safety features.

2. **Analysis of SMR Opportunities in the Yukon:** The information collected on SMR technologies is assessed for its suitability in different use scenarios according to the assessment criteria detailed in Section 2.3. Three potential use scenarios are identified based on the forecasted electricity requirements in the territory as the Yukon seeks to increase electrification, reduce its GHG emissions, and foster a green economy.

3. **Key Requirements for SMR Viability in the Yukon:** The key findings pertaining to the opportunities, benefits, and challenges of SMR deployment in the Yukon are summarized in consideration of the identified use cases for the technology in the Yukon.

2.2 Analysis Basis

2.2.1 Yukon Emissions

Although the Yukon's GHG emissions represent a small portion of the total Canadian emissions, the per person emissions in 2019 were the sixth highest in Canada at approximately 18.9 tonnes CO_2 equivalent (CO_2e) per person [8].

According to the latest report on *Greenhouse gas emissions in Yukon: 2019* [8], the Yukon's total GHG emissions increased by 14 percent from 2010 levels to 783 kilotonnes (kt) of CO_2e. As shown in Figure 1, on-road emissions from diesel and gasoline vehicles accounts for 55 percent in 2010 and 56 percent in 2019. Over this period, the emissions from on-road gasoline increased by 41 percent. Emissions from on-road diesel and heating fluctuated slightly year-to-year as shown in Figure 2.

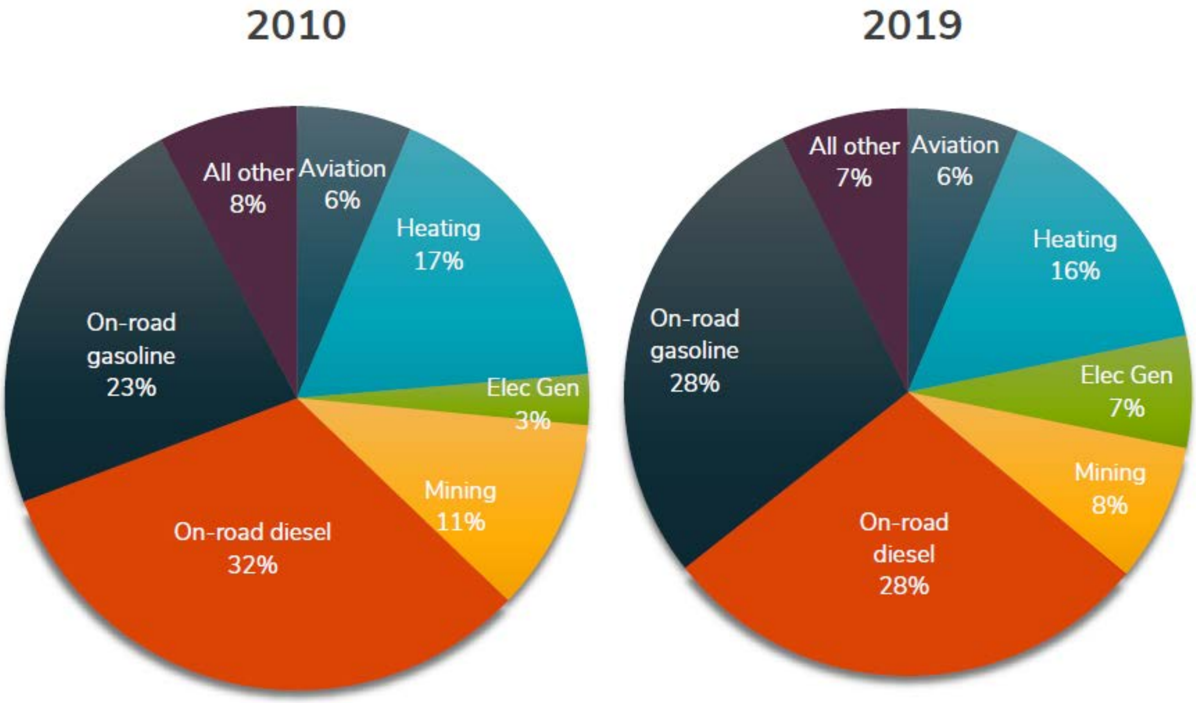

Figure 1: Yukon Emissions by Source in 2010 and 2019 [8]

Emissions from electricity generation increased by 160 percent from 2010 emission levels to 7 percent of the total Yukon emissions in 2019. This was largely driven by an increased use of thermal generation capacity including liquefied natural gas (LNG) and diesel generation due to low renewable generation capacity during the winter months [9, 10, 11]. The emissions from mining also varied year-to-year as shown in Figure 2 and are considered a potential driver of annual variation in conjunction with aviation and on-road diesel emissions [8].

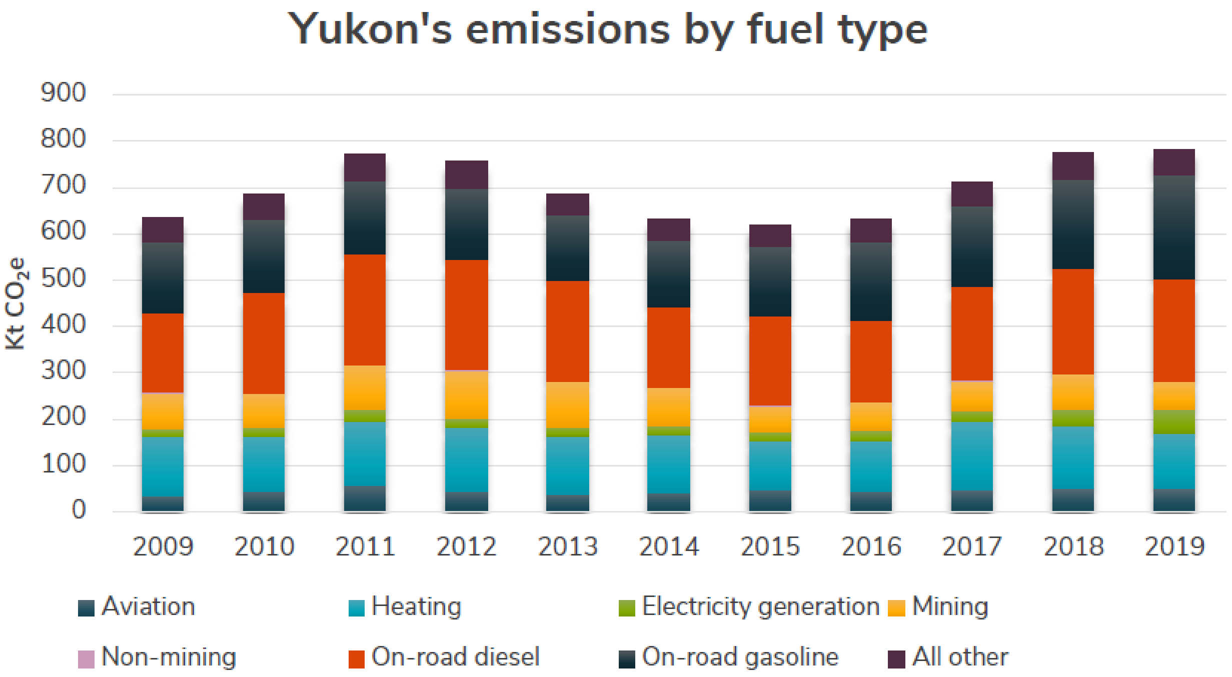

Figure 2: Yukon Emissions by Source Between 2009 and 2019 [8]

Further information and data on the Yukon emissions can be found in *Greenhouse gas emissions in Yukon: 2019* [8].

2.2.2 Yukon Emission Reduction Targets

In 2020, the Government of Yukon released its climate strategy entitled *Our Clean Future: A Yukon strategy for climate change, energy and a green economy* [1], in which, the Government of Yukon committed to reducing GHG emissions from transportation, heating, electricity generation, other commercial and industrial activities, waste and other areas to 30 percent of 2010 levels by 2030. In 2021, the Government of Yukon increased the reduction target to 45 percent by 2030, compared to 2010 levels in recognition of the urgency of the climate crisis [12].

Some key components of the Yukon strategy for meeting this target are the reduction of heating and electricity generation emissions from carbon intensive sources in favour of green infrastructure. As such, the Government of Yukon has set three goals related to green energy and heating [12]:

- Generate 97 percent of the electricity on the Yukon's main grid from renewable sources with a regulatory requirement of 93 percent renewable generation by 2030;
- Reduce diesel use for electricity generation by communities that are not connected to the main electricity grid by 30 percent by 2030, compared to 2010; and
- By 2030, meet 50 percent of heating needs with renewable energy sources.

As discussed later in Section 4.4, each of these targets are expected to benefit from the deployment of SMR technologies in the Yukon since SMRs provide non-emitting electrical generation capacity as well as waste heat that can be used in other applications.

> "Our approach to energy production will see more renewable energy produced for both heating and electricity, combined with upgrades to the electricity grid and energy storage to make the best use of seasonal resources. This will allow us to continue to heat and power our lives with clean energy even as electricity demand grows and as we use more electricity for transportation and heating." - *Our Clean Future: A Yukon strategy for climate change, energy and a green economy* [1]

For transportation, the Government of Yukon set a target of at least a 30 percent reduction in emissions from transportation by 2030 compared to 2010. The Yukon strategy for meeting this target consists of efficiency improvements to reduce demand, the use of clean electricity zero emission vehicles for some transportation needs and using cleaner transportation fuels. The electrification of transportation within the Yukon is expected to increase the amount of electricity required and is considered in the planned grid capacity and green generation requirements.

> "It is important to increase the amount of electricity we produce from renewable sources as electricity demand grows and as we increasingly use electricity for transportation and heating needs." - *Our Clean Future: A Yukon strategy for climate change, energy and a green economy* [1]

At the time of writing, the Government of Yukon is engaging with the mining industry, First Nations governments, environmental groups, and the public on the development of intensity-based emissions targets for the mining sector [13]. The Government of Yukon is proposing a mining emissions intensity reduction target of 45 percent per unit of production by 2035. For the purposes of this project, it is assumed the proposed target is accepted, however, the final target should be considered in future mining projects within the Yukon.

Emissions modeling from the *Our Clean Future 2020 Annual Report* [12] suggests that the actions in *Our Clean Future* [1], along with federal policies and programs, are expected to reduce 2030 GHG emissions by approximately two-thirds of the 45 percent target. As such, additional emission reduction measures beyond the commitments of *Our Clean Future* and associated annual reports are needed to achieve the Yukon emissions reduction target.

2.2.3 Yukon Electrical Infrastructure

The existing electrical generation and transmission infrastructure in the Yukon is shown in Figure 3. As of 2020, the Yukon electrical infrastructure consists of [14]:

- One large hydroelectric based grid called the Yukon Integrated System (YIS) (i.e., the Yukon grid)
- One medium sized diesel-based grid serving Watson Lake; and
- Three smaller isolated communities with diesel generation (Beaver Creek and Destruction Bay/Burwash Landing) and solar/diesel generation (Old Crow).

All of these are islanded grids, meaning that they cannot rely on neighboring grids to supply electricity when resources are limited and must have sufficient capacity to meet energy needs. In recent years, the Yukon has turned to rented diesel generators to meet the YIS energy needs during the winter months due to low water levels in Aishihik Lake [9, 10, 11]. Three diesel generators are also set to retire before 2030.

Figure 3: Yukon Electrical Generation and Transmission [14]

ATCO Electric and the Yukon Energy Corporation (YEC) are responsible for essentially all of the electricity generation and transmission within the Yukon. YEC is the main generator and transmitter of electricity in the Yukon with 132.65 MW of installed capacity [15]. ATCO Electric is a low voltage distributor which purchases the majority of its power from the YEC for distribution to consumers. ATCO also owns and operates one hydro-electric plant (1.3 MW) and various diesel facilities (14.6 MW total) in the Yukon, including those that power the remote communities [15].

YEC has developed forecasts for the peak non-industrial capacity demand and dependable peak generation capacity (under N-1 conditions[1]). These projections include the dependable capacity from existing diesel and LNG resources and do not consider their replacement with dependable green generation options to meet emissions targets. The gap between the dependable generation capacity and the peak demand is forecasted to be significant as shown in Figure 4.

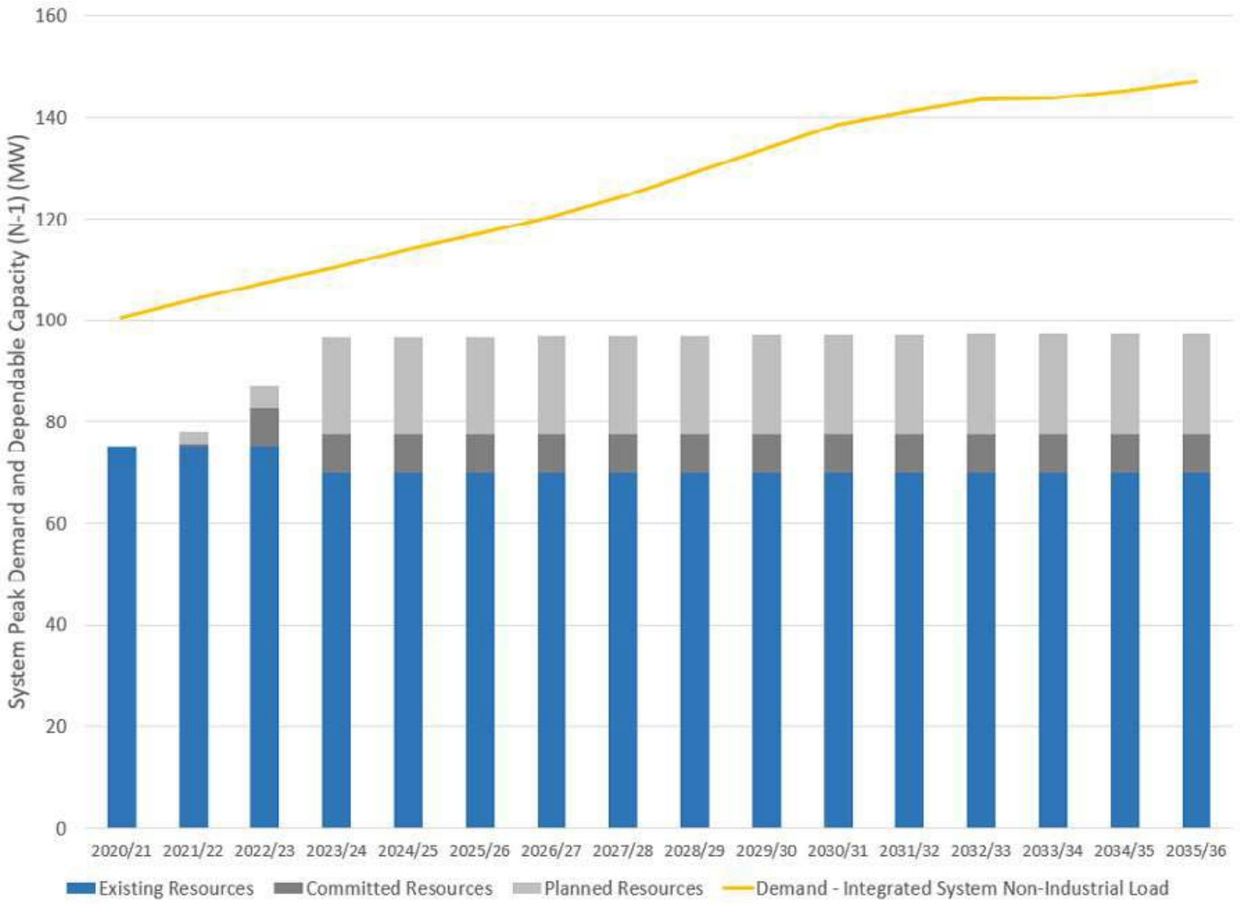

Figure 4: Annual Capacity Gap Analysis under N-1 Conditions [14]

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[1] N-1 refers to the Single Contingency Planning Criterion, which is a reliability planning criterion used to determine the capacity requirements of the system. YEC's N-1 criterion requires that each part of the YEC transmission grid should be able to carry the forecast peak winter demand, excluding major industrial demand, under the largest single contingency.

To meet the growing demand for clean electricity, YEC has developed a *10-Year Renewable Electricity Plan* [14] which includes a series of projects summarized in Table 1. These projects represent stages 1 and 2 of the action plan and result in an increased dependable capacity as shown in Figure 5. A third stage, stage 3, is focused on the development and implementation of future potential resources.

This feasibiity study is conducted with the assumption that these projects will proceed as planned.

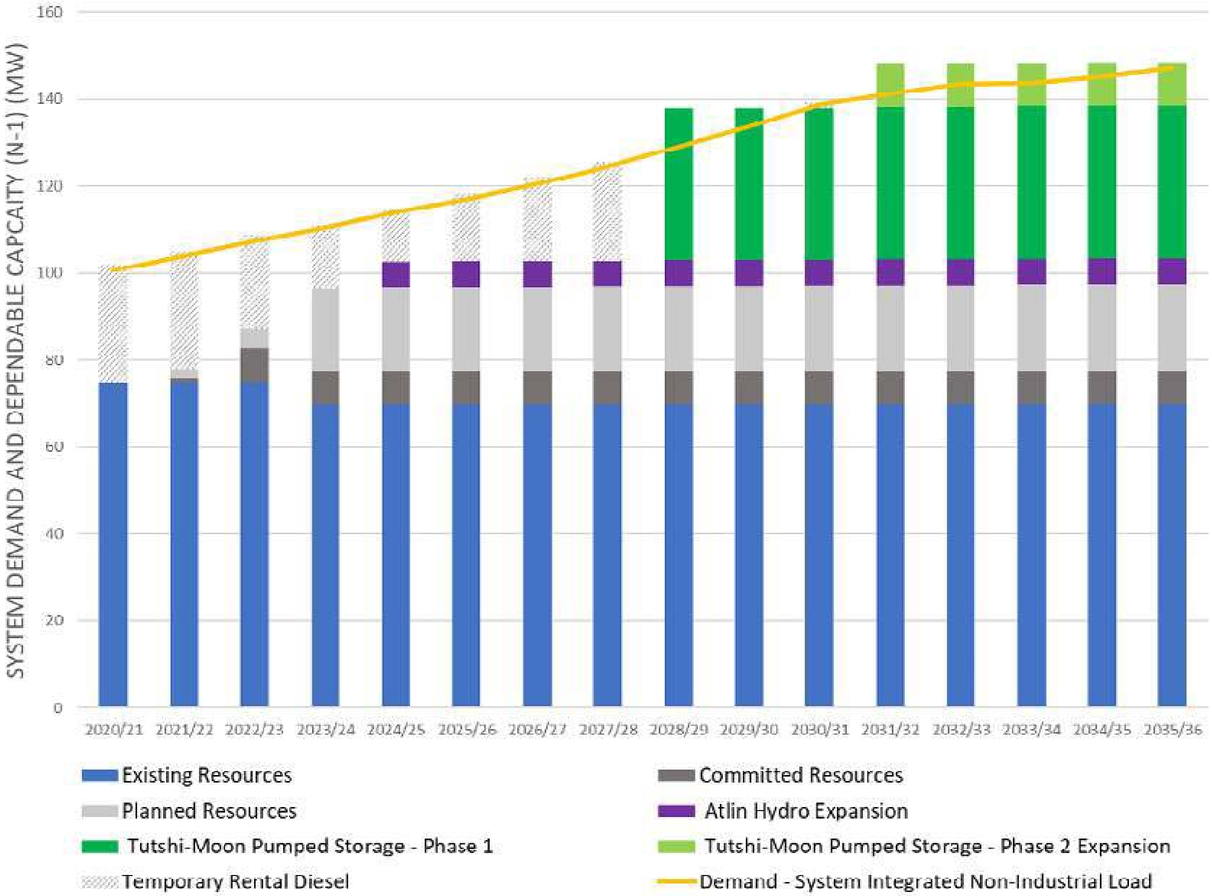

Figure 5: 10-Year Renewable Electricity Plan Base Case Portfolio Capacity [14]

Table 1: YEC Renewable Electricity Plan Projects
(Excerpts from YEC 10-Year Renewable Electricity Plan [14])

Stage	Project	Project Description
Projects Under Development	Whitehorse Hydro #2 Uprate	The Whitehorse Hydro WH2 Uprate Project will increase the efficiency and maximum capacity of the WH2 generation unit, resulting in more generated electricity for the same water throughput. The WH2 Uprate Project at the Whitehorse generating station will provide 6.2 GWh of annual energy and at least 0.64 MW of dependable capacity.
	Battery Storage	On September 5, 2019, the Government of Canada committed $16.5 million towards the construction of a new battery storage system in Yukon. The new battery, which is currently projected to be sized at 8 MW/ 40 MWh, will help meet growing peak demands for power while displacing diesel and improving grid reliability.
	Independent Power Producers Standing Offer Program (SOP)	The SOP is outlined in the Independent Power Production (IPP) Policy of the Yukon territorial government issued in 2015. The SOP included in the 10-Year Renewable Electricity Plan envisions 40 GWh/year of energy delivered by the IPP sector by the year 2024 and continuing past the end of the planning period. Since it is assumed that the SOP projects will most likely be intermittent renewable resources such as wind and solar, no dependable capacity is assigned to these resources.
	Micro-Generation Program	The Micro-Generation policy issued by the Yukon government in October 2013 outlines this program. The policy is applicable to projects up to 50 kW. The micro-generation included in the 10-Year Renewable Electricity Plan envisions 6.5 GWh/year of delivered energy by the year 2024 and continuing past the planning period. Similar to the IPP SOP, no dependable capacity is assigned to micro-generation projects because they will be comprised of intermittent renewable resources such as wind and solar.
Planned Projects	Whitehorse Hydro #4 Uprate	This project will increase the maximum water flow at WH4, resulting in an increased maximum output. The WH4 Uprate Project at the Whitehorse generating station will provide 0.9 GWh of annual additional energy. Although this project increases the maximum capacity of the unit, it does not provide additional dependable capacity due to winter ice flow restrictions.
	Southern Lakes Enhanced Storage Project (SLESP) and Mayo Enhanced Storage Project (MLESP)	The SLESP will expand the storage range on the Southern Lakes system, which provides water (i.e., fuel) storage for the Whitehorse generating station. This will be achieved by decreasing the licensed Low Supply Level by up to 10 cm and increasing the licensed Full Supply Level by up to 30 cm. Although the SLESP is a water storage project that does not generate electricity itself, it will enable generation of an additional 6.5 GWh of electricity each year at the Whitehorse Hydro facility. The MLESP project seeks to enhance water storage at Mayo Lake by lowering its current licensed minimum level by up to one metre. The MLESP would generate an additional 4 GWh of electricity each year.

Stage	Project	Project Description
Planned Projects (cont.)	Incremental Diesel Replacement	By replacing retired diesel generator units at existing generation facilities, YEC can reduce the need for rental diesel generators from November through March. The total replacement diesel assumed over the planning period amounts to 12.5 MW.
	Demand Side Management (DSM) Programs	DSM involves using incentives, electricity rate structures, and building and appliance codes and standards to encourage customers to reduce the amount of electricity they use. In 2014, YEC and ATCO Electric Yukon jointly launched and operated a DSM program called inCharge which provided rebates and electricity savings kits. However, the YUB denied the costs of this program in its decision on YEC's 2017-2018 General Rate Application. As a result, YEC's DSM activities are on hold pending confirmation that future DSM costs will be allowed. The focus of a relaunched DSM program would be on measures that deliver peak capacity savings (i.e., reductions in peak electricity consumption). A suite of programs has been developed which will be implemented once there is regulatory certainty about allowing of future DSM-related costs. The DSM programming is forecast to provide up to 6.7 GWh of annual energy and 7 MW of dependable capacity by 2030.

Other communities in the Yukon not connected to the Yukon grid rely on diesel generation to supply electricity to a local micro-grid. The electrical generation in these communities has high fuel costs associated with the transportation of fuel and is vulnerable to increases in the cost of fuel.

Solar generation capacity has also been installed in Old Crow to offset some of the summer demand, however, this capacity is not considered dependable since it is not available year-round.

In addition to the Yukon grid and microgrid communities, off-grid mine sites represent a significant electricity demand within the Yukon.

2.2.4 SMR Roadmap

The SMR roadmap, a 10-month engagement process with stakeholders and potential end-users, was released in November 2018 to study and identify the opportunities for SMR's in Canada [16]. The project was led by the Canadian Government in conjunction with stakeholder groups consisting of interested provinces, territories, and energy utility companies. Through different expert working groups and workshops throughout Canada, a large amount of feedback and recommendations were received for the direction of SMR deployment in Canada. The 5 key findings from the SMR roadmap are described below [16]:

1) Successful SMR deployment will likely require a 'fleet' based approach to operations in order to benefit from standardization and economies of multiples (i.e., capital costs decrease as more units are produced).

2) Demonstrating SMR technology in Canada is key to capturing first mover advantage. Canada's three applications will likely have different demonstration 'tracks'.
3) Appropriate risk sharing among governments, power utilities, and industry will be necessary for SMR demonstration and deployment in Canada.
4) Public and Indigenous groups, as well as other potential end-users, have concerns about safety, waste management, and overall cost of SMRs. Ongoing engagement and knowledge-sharing will be important as more information on SMRs becomes available.
5) Canada's regulatory framework and waste management regime are well-positioned to respond to the SMR paradigm shift, but some modernization will be necessary to reflect the reality of the smaller size of an SMR.

Further information on these findings can be found in *A Call to Action: A Canadian Roadmap for Small Modular Reactors* [16].

2.2.5 SMR Action Plan

In 2020, the Government of Canada launched the SMR Action Plan, outlining the progress and ongoing initiatives for the implementation of the goals set out in the SMR roadmap [17]. There are many organizations and partners involved in the action plan, including various provinces and territories, municipalities, Indigenous groups, power utility companies, industries, engineering firms, and academic, civil society, educational, and research institutions. Each partner has their own chapter in the action plan outlining the actions they will be taking to help with the implementation of SMR's in Canada [17].

On December 18, 2020, the Government of Yukon sponsored the SMR action plan [18]. The Government of Yukon's chapter in the action plan discussed their support for SMR deployment in Canada:

> "The Government of Yukon supports the vision for SMR development in Canada as laid out in the SMR Roadmap and action plan. Our government endorses the action plan statement of principles and sees the potential for SMRs to be a source of clean, safe, and affordable energy with economic benefits for Canada." – *SMR Action Plan – Yukon Partner Chapter* [18]

2.2.6 Potential Use Scenarios

This section summarizes the potential use scenarios used to assess the opportunities, benefits, and barriers to SMRs in the Yukon. Three (3) potential use scenarios are identified as most applicable to the Yukon including:

- Connected to the Yukon Grid;
- Powering a remote off-grid mine site; and
- Connected to a microgrid community.

For this analysis, these scenarios are used to analyze various aspects related to the deployment of SMRs in Yukon. The analysis may assess one or multiple potential scenarios at a time where commonalities exist between scenarios for a particular assessment criterion. For example, SMRs deployed at remote mine sites have many commonalities with SMRs connected to microgrid communities.

The elements unique to each potential use scenario are established in the following subsections. These elements include electrical generation requirements, existing generation capacity and sources, load characteristics, seasonality, grid connectivity, SMR deployment location(s), transportation and accessibility, and potential thermal loads.

2.2.6.1 Yukon Grid Connected Scenario

This section discusses the characteristics of the scenario for the deployment of SMRs on the YIS (i.e., the main Yukon grid). In the Yukon, all but 5 remote communities are connected to the YIS. The YIS grid is currently powered by hydro, solar, LNG, and diesel. Hydro currently provides the bulk of the total energy, accounting for 93.4 MW of the 156.6 MW total Yukon capacity [15]. Section 2.2.3 provides further discussion on the current Yukon electrical infrastructure and planned renewable energy projects to meet the increasing energy demand in the Yukon.

The grid connected scenario will explore the opportunity of how an SMR can provide base load power for the main Yukon grid. The SMR is assumed to be located near a main population center (e.g., Whitehorse) and associated electrical infrastructure for centralized generation and have a power output of 100 MWe based on the Yukon's electrical capacity requirements. A capacity factor of 80% is assumed for the SMR, which corresponds to the ratio of the total energy produced to the energy that could be produced if the reactor is always running at maximum production. A 40-year operational life for the SMR is assumed for this scenario.

2.2.6.2 Remote Off-Grid Mine Site Scenario

This section defines the characteristics of the off-grid mine site scenario based on a representative mine site from the *Small Modular Reactor (SMR) Economic Feasibility and Cost-Benefit Study for Remote Mining in the Canadian North: A Case Study* [19]. This study uses detailed engineering data and projections from a mining company and builds on the public-domain reports by Hatch Ltd. [20], the Natural Resources Canada SMR Roadmap [16] and the associated report from the Economic and Finance Working Group (EFWG) of the SMR Roadmap [21].

Currently, there are 10 off-grid operating mines in Canada, and most are served by diesel generators. Diesel generators have historically been used for off-grid mines since they are reliable, fast acting, and the output can be easily varied; however, a significant downside is that they require large amounts of fuel and are GHG emitting. The potential for renewable energy options at off-grid mine sites has been investigated. Hydro energy has large seasonal variation and requires a water body with a difference in elevation, making it a rather difficult energy option to deploy at mine sites. Solar energy also suffers from seasonal variation, which leads to the concern of inconsistent energy production. Hybrid solar-diesel systems have also been explored for mine sites. However, these systems require diesel to constantly run near their minimum load to provide during situations where the power from the solar system drops, and this results in a low renewable energy penetration (share of renewable capacity in relation to total peak quantity of the system) [22].

At off-grid mine sites, there is a need for self-sufficiency and consistent energy production due to the remoteness of the locations. To ensure this need is met, extra diesel generation capacity is typically added above the peak load due to on-line load variations, off-line maintenance, and any unplanned system failures. This results in the installed diesel capacity being almost twice the peak requirement.

This potential use scenario explores the opportunity for SMR technologies to meet the needs at off-grid mine sites similar to those in this representative mine site being used. For this scenario, a 25-30 MWe SMR is considered. A 20-year operational life is assumed for this use scenario and is a good estimate for the lifespan of a representative mine site.

2.2.6.3 Microgrid Community Scenario

This section discusses the potential use scenario in microgrid communities. As mentioned in Section 2.2.6.1, there are five communities in the Yukon that are not connected to the Yukon grid. These communities are served by four microgrids, which have historically been powered solely by diesel generators [15]. The microgrid communities include Beaver Creek, Burwash Landing and Destruction Bay, Watson Lake, and Old Crow, and all are remote from the rest of the Yukon’s communities. This is especially true for Old Crow, which is much further North than the other communities and typically only accessible by air [15]. As of 2021, Old Crow has had a fully operational solar farm that provides up to 24 percent of the community’s annual power needs [23]. An ice road to access Old Crow is installed in occasional winters and open for a few weeks to bring in large supplies and help support big projects. The construction and maintenance of this ice road is itself a major construction project, which is why it is not done annually and only open a few weeks at a time. The four diesel generators that power these communities account for a total capacity of 7.5 MWe, with a maximum of 5 MWe for Watson Lake and a minimum of 0.7 MWe for Old Crow [15].

Microgrid communities experience high costs for fuel transportation. This potential use scenario explores how SMR technologies can be employed in these remote communities and limit the need for frequent fuel transportation. The SMRs considered have a generation capacity of less than 5 MWe per the energy requirements of these remote communities and are capable of load following to meet the different seasonal demands. There is the possibility for diesel to be used for peak shaving during times of maximum demand. It is noted that there are SMR technologies under development with sub-MW outputs which could find use in small remote communities with small energy requirements (e.g., Old Crow).

2.3 Assessment Criteria

This section establishes the criteria used to assess the feasibility of SMR deployment in the Yukon. The assessment criteria include:

- **Logistical Considerations:** Logistical supply chain considerations for the construction and operation phases of the project (transportation to remote locations, availability of personnel, equipment, infrastructure, etc.).
- **Fuel Availability:** Fuel supply chain considerations, the interim storage of spent fuel or other high level radioactive waste, and other waste management considerations.
- **Technology and Infrastructure Availability:** Commercial availability of the technologies under consideration for potential deployment in Yukon for the different use cases. The recommended sizes for SMRs in the Yukon are described, building on the discussion of the SMR Technology Review Section.
- **Benefits:** Identification of the benefits from deploying an SMR for the different potential use scenarios.
- **Cost and Competitiveness with Other Electricity Sources:** Economic analysis of the cost of generation over the life of the project. The cost comparison will include comparison to other electricity sources, such as existing fossil fuel plants, and renewable sources.
- **Regulatory Readiness:** Consideration of the regulatory processes required to develop an SMR project in the Yukon, including Environmental Assessment requirements specific to Yukon and at the federal level.
- **Public Perception:** The results of outreach activities undertaken to document the current status of public perception of SMRs in the Yukon, and related implications to feasibility.

3. SMR TECHNOLOGY REVIEW

3.1 Overview of SMRs

SMRs are advanced nuclear reactors with an electrical generation capacity of up to 300 MWe per unit and produce baseload power without the emission of greenhouse gases. This electrical generation capacity is significantly smaller than conventional nuclear power plants. For example, Bruce Power's eight units have an electrical capacity of 6400 MWe [24], and the Darlington Nuclear Generating Station's four units have an electrical capacity of 3500 MWe [25]. However, SMRs are 'modular' meaning that multiple SMR units may be installed to further increase generation capacity as needed. Units are designed so that most of the fabrication occurs in the factory prior to being transported and installed at a prepared location. These features greatly benefit SMR deployment timelines and reduce the capital costs compared to traditional nuclear power plants built with economy of scale in mind. SMRs are designed with public safety and environmental protection as the utmost priority and include passive safety systems that are considered "walk-away" safe for extended periods. Walk-away safe provides inherent safety as it means that, if all power is lost, the nuclear reactor will automatically shutdown without any human action needed, and meltdown of the core will not be possible.

SMRs operate year-round and compliment electrical generation from renewable sources. Many SMR designs have load following capabilities and are thus capable of smoothing seasonal and intermittent electrical generation from sources such as solar and wind. Load following capabilities are also useful as stand-alone generation systems in locations where diesel generation is typically used such as at mine sites and remote communities.

Within Canada, multiple SMR projects are currently progressing in Ontario, New Brunswick, and Saskatchewan for the planned deployment and operation of SMRs ranging from 5 to 300 MWe of generation capacity between 2027 and the early 2030's.

There are many different vendors that currently have SMR designs going through the CNSC pre-licensing vendor design review and licensing processes in Canada. The following Section 3.2 discusses many of these vendor designs, categorized by the reactor technology they utilize.

3.2 SMR Technologies

This section provides an overview of various SMR designs and features including:

- Technology and design;
- Design safety features;
- Fuel type;
- Load following and base load capabilities;
- Electrical and thermal capacity (size); and
- Project lifespan.

This section is broken down by technology subsections and identifies the applicable use scenario(s) for each SMR design discussed.

3.2.1 Boiling Water Reactors

A boiling water reactor (BWR) is a nuclear reactor where the reactor core heats water and turns it into steam, which is then used to drive a steam turbine and generate electrical power. The steam exiting the turbine then passes through a condenser where it returns to the liquid state and is sent back to the reactor core, completing the loop. One example of a BWR type SMR undergoing the pre-licensing vendor design review and licensing processes in Canada is the BWRX-300 from GE Hitachi [26]. This SMR design is the tenth evolution of the original BWR and is selected for grid scale generation in Ontario [27] and Saskatchewan [28]. The design features for the BWRX-300 are summarized in Table 2.

Table 2: Features for the BWR SMR design, the BWRX-300

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
BWRX-300	3.81-4.95% U-235 enriched GNF2 fuel assembly	**60-year operational life** [29] 24-to-36-month construction time [29] Natural circulation and passive cooling isolation condenser system [29] Base load/Load following [26]	300	Passive safety cooling (7 days) [26]

3.2.2 Molten Salt Reactors

A molten salt reactor (MSR) is a nuclear reactor that uses molten fluoride salts as the coolant. Molten salts are very thermally stable and using them as a coolant allows for low pressure and high temperature operation [30]. Both factors allow for decreased costs, increased safety, and an increased efficiency in generating electricity [31]. Two examples of MSR type SMR designs that have made progress in the pre-licensing vendor design review and licensing processes in Canada are the Integral Molten Salt Reactor (IMSR) from Terrestrial Energy and the Moltex Energy Stable Salt Reactor – Uranium (SSR-U) and Stable Salt Reactor – Wasteburner (SSR-W). The design features for these SMR designs are summarized in Table 3.

Table 3: Features for the MSR SMR designs, the IMSR and Moltex Energy SSR.

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
IMSR	Standard uranium nuclear fuel (low enriched uranium - <5%) [30]	**>50-year operational life** [30] Flexible application – electrical and/or process heat [30] Reactor core has a 7-year life span [30] Base load/Load following [30]	200	"Walk away" safe [30] All primary reactor components, including the graphite moderator, are sealed into a replaceable reactor core [30]

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
SSR-U	Enriched uranium (6%) [32]	**~50-year operational life** [33] 16-20 year refueling cycle [33] Heat can be used to support efficient hydrogen production processes, flexible application [32] Thermal spectrum reactor which generates heat at higher temperatures [32] Base load/Load following [32]	Modular capacity (16 MWe/unit)	Passively cools in all scenarios [32] No contained pressure [32] Self-damping, reaction slows as temperature rises [32]
SSR-W 300	Recycled nuclear waste [32]	Fast reactor that uses recycled nuclear waste as fuel [32] Base load/Load following [32] Heat can be used to support efficient hydrogen production processes, flexible application [32]	300	

3.2.3 High-Temperature Gas Reactors

A high-temperature gas-cooled reactor (HTGR) is a nuclear reactor that operates at very high temperature, utilizing a once-through uranium fuel cycle. Outlet temperatures for an HTGR can reach temperatures of greater than 750 °C. A graphite moderator, which allows the nuclear reaction to be sustained, is used as it has high heat absorption, high thermal conductivity, and low neutron absorption [34]. HTGRs typically use helium as a coolant which is inert and promotes safety [34]. There are multiple HTGR type SMR designs undergoing the pre-licensing vendor design review and licensing processes in Canada, including the U-Battery, the Xe-100 from X-energy, the StarCore from StarCore Nuclear, and the Micro Modular Reactor (MMR) from Ultra Safe Nuclear (USNC). The design features for these SMR designs are summarized in Table 4.

Table 4: Features for the HTGR SMR designs U-Battery, Xe-100, StarCore and the MMR.

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
U-Battery	TRISO uranium particle fuel [35]	Deployable off grid [35] Footprint of 350 m^2 [35] Flexible application for heat, hydrogen production and water desalination [35] 2-year construction period for a single unit plant [36] Load following [35]	4	Size and design promote inherent safety [35] Structure and shape of TRISO fuel maintains integrity under extreme conditions [35]

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
Xe-100	TRISO uranium particle fuel [37]	**60-year operational life** [37] Flexible application (electrical and/or process heat) [37] Online refueling [37] High temperature tolerant graphite core structure [37] 400-yard safety perimeter [37] Base load/Load following [37]	80	Passively cools in all scenarios, cannot melt down. [37] Structure and shape of TRISO fuel maintains integrity under extreme conditions [37]
MMR	Ultra-Safe's FCM fuel pellets [38]	**20-year operational life** [38] Helium gas coolant [38] 5-acre site area [38] District heating, desalination, and process heat are all possible [38] Can operate stand-alone or connected to grid [38] Operates at constant power, but electricity and heat are delivered on demand [38]	5	Passively cools in all scenarios, cannot melt down. [38] Does not require power to operate [38] Reactor naturally shuts down in all accident conditions [38] Fission products are locked inside the FCM fuel permanently, during and after power production [38] Helium coolant is inert, no boiling or flashing, and does not react with any core components [38]

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
StarCore	TRISO uranium particle fuel [39]	Helium gas coolant [39] Applicable to remote locations [39] District heating, desalination, and process heat are possible [39]	10-14	Automatic shutdown, no human intervention is required [39] Structure and shape of TRISO fuel maintains integrity under extreme conditions [39] Inert coolant [39]

3.2.4 Pressurized Water Reactors

A pressurized water reactor (PWR) is a nuclear reactor where water is pumped to the reactor core, under high pressure, and is heated by the energy released from the fission of atoms. The pressurized water does not boil, but instead flows to a steam generator where it heats low pressure water in a secondary loop, which then turns to steam and drives a turbine that generates electrical power. Two examples of PWR type SMR designs that have made progress in the pre-licensing vendor design review and licensing processes in Canada are the SMR-160 from Holtec International, and Nuscale Integral Pressurized Water Reactor from Nuscale Power. The design features for these SMR designs are summarized in Table 5.

Table 5: Features for the PWR SMR designs SMR-160 and Nuscale

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
SMR-160	Commonly available enriched uranium fuel [40]	**80-year operational life** [40] 4.5-acre footprint for 1 unit, 6 acres for 2 units [40] Primary system based on natural convection circulation [40] On-site underground storage of used fuel [40] 36-month construction period for first unit [40] Flexible application for district heating, water desalination, hydrogen generation, and off grid use [40] Base load/load following [40]	160	Passive cooling, “walk away” safe [40] Robust and resistant containment enclosure structure [40] No active components (pumps) needed to run the reactor [40] Reactor core is underground [40] Reactor system designed to withstand extreme events [40] Gravity driven fluid flow [40]

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
Nuscale Integral Pressurized Water Reactor	Standard LWR fuel in 17 x 17 configuration, each assembly 2 meters (~ 6 ft.) in length. Fuel enriched at less than 5 percent uranium [41]	Digital Instrumentation & control system to monitor and control all plant systems in a single control room [41] Reactor is 65 feet tall x 9 feet in diameter [41] Capacity factor >95% [41] Base load/Load following [41]	77	Passive cooling indefinitely, “walk away” safe [41] No power required for shutdown [41] High pressure containment vessel [41] Passive decay heat removal [41] No pumps [41] Containment vessel submerged in a heat sink within a seismic category 1 reactor building [41]

3.2.5 Lead-Cooled Fast Reactor

A lead-cooled fast reactor (LFR) uses a molten lead or lead-bismuth eutectic coolant [34]. They operate near atmospheric pressure, which promotes inherent safety. One drawback of LFRs is the corrosive nature of molten lead when it hits 500 °C, which requires a mitigation strategy [34]. Lead also has a high melting point, and is liquid during reactor operations, so systems must be in place to prevent lead from solidifying during reactor shutdown [34]. Lead-bismuth cooled reactors generate Po-210 by activation of Bi-209. Po-210 is a pure alpha emitter that tends to disperse itself, making contamination control challenging [42]. There are two LFR type SMRs designs by LeadCold Reactors that are currently undergoing the CNSC pre-licensing vendor design review and licensing processes. The design features for these SMR designs are summarized in Table 6.

Table 6: Features for the Lead-Cooled Fast Reactor SMR SEALER designs.

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
SEALER-Arctic	2.4 tons of 19.9% enriched uranium oxide [43]	**Operational life between 10 and 30 years** [43] Fuel never replaced during operation [43] Base load/Load following	3-10	Removal of decay heat from the core by natural convection of lead coolant [43] If an accident occurs, volatile fission products are retained in the lead coolant [43] Dip coolers are activated to transport residual heat and ensure reactor remains in normal temperature range [43] No violent exothermic reaction with water [43] Very high boiling temperature, reducing the risk of loss of coolant [43]
SEALER-55	21 tons of 12% enriched uranium nitride [43]	**Operational life of 25 years** [43] Fuel never replaced during operation [43] Base load/Load following	55	

3.2.6 Sodium-Cooled Fast Reactor

A sodium fast reactor (SFR) uses a liquid sodium metal coolant. They operate at near atmospheric pressure, which provides inherent safety [34]. They can operate at higher temperatures, resulting in a higher thermal efficiency and high thermal conductivity with metallic fuels. One drawback for SFRs is the hydrogen producing chemical reaction of sodium with water, requiring an additional heat exchange loop and extra care in the creation of the steam generator [34]. One example of an SFR type SMR that is currently undergoing the pre-licensing vendor design review and licensing processes with the CNSC is the ARC-100 from Arc Clean Technology. The design features for this SMR are summarized in Table 7.

Table 7:Features for the Sodium-Cooled Fast Reactor ARC-100 SMR.

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
ARC-100	Metallic uranium alloy fuel [44]	**60-year operational life** [44] 20 year refueling cycle [44] Flexible application for district heating and hydrogen production [44] Consumes its own waste and fuel over and over, significantly reducing the amount of long-term waste. Can also recycle waste from traditional reactors to generate energy [44] Load following [44]	100	Passive cooling, "walk away" safe [44] Low pressure operation [44]

3.2.7 Heat Pipe Reactors

A Heat Pipe Reactor (HPR) is a newer concept that has been designed and proposed for application in areas that require small amounts of highly reliable power [34]. These reactors utilize heat pipes to transfer the heat from the reactor core to the power conversion unit without the need for additional components such as pipes or valves [34]. Heat pipes are closed tubes that contain a working fluid that allow for the transfer of heat through evaporation and condensation [34]. Therefore, the coolant, typically sodium or potassium, is contained within the heat pipe and does not contact any fuel elements [34]. One example of an HPR type SMR that is currently undergoing the pre-licensing vendor design review and licensing processes with the CNSC is the eVinci Microreactor from Westinghouse. The design features for this SMR are summarized in Table 8.

Table 8: Features for the Heat Pipe eVinci Microreactor

Design	Fuel Type	Design Specific Features	Electrical Output (MWe)	Safety Features
eVinci microreactor	TRISO uranium particle fuel [45]	**40-year operational life** [45] 3+ year refueling cycle [45] Fully factory built, fueled, and assembled [45] Less than 30 days on-site installation [45] Autonomous operation [45] Designed for off grid communities and operations [45] Load following [45]	1-5	Near zero emergency planning zone with small site footprint [45] High reliability and minimal moving parts [45] No spent fuel or waste storage on site [45]

4. ANALYSIS OF SMR OPPORTUNITIES IN THE YUKON

This section analyzes the feasibility of three potential use scenarios (Section 2.2.6) for the deployment and uptake of SMRs in the Yukon. Information from applicable SMR reactors and projects underway in Canada is used to provide example information for the different potential use scenarios, where applicable. While these projects and technologies are used as examples due to readily available information, there are many other SMR's currently being designed or going through CNSC pre-licensing vendor design review and licensing processes. In the context of the feasibility analysis, example information from current Canadian SMR projects is expected to provide a reasonable representation of other designs with similar electrical generation capacities.

4.1 Technology and Infrastructure Availability

This section describes the timelines for commercial availability and potential deployment of SMRs for the potential use cases and technologies under consideration. The recommended sizes for SMRs in the Yukon are described, building on the recommendations in the initial literature review section.

Many SMR vendors are currently completing Pre-Licensing Vendor Design Reviews (VDRs) with the CNSC to verify the acceptability of their nuclear reactor designs in accordance with Canadian regulatory requirements. The review consists of three phases: Pre-licensing agreement of compliance with regulatory requirements, pre-licensing assessment for any potential fundamental barriers to licensing, and follow-up [7]. A pre-licensing VDR is carried out within a service agreement between the CNSC and reactor vendor [7]. Currently, there are 10 SMR reactor designs that are within either Phase 1 or Phase 2 of their VDR with the CNSC, all of which have been described in Section 3.2. The duration of these review phases can vary depending on the vendor's proposed schedule; however, a Phase 1 review typically takes 12-18 months, and a phase 2 review takes 24 months [7]. There are an additional 2 SMR designs that are in the process of applying for a service agreement to begin their VDR, one being the eVinci microreactor [7], which is used in this study as an example for microgrid communities. The application process typically takes a few months but can vary depending on multiple factors [7].

It is expected that within the next decade, there will be many SMR vendor designs that have completed the VDR and are ready to move forward with construction licence applications, where applicable. Completing a Phase 2 VDR increases the efficiency of technical reviews as they relate to the licence to construct [7]. The following sub-sections will discuss the exact timelines of current projects and SMR designs being deployed that have been used as examples for each potential use scenario.

4.1.1 Yukon Grid Connected Scenario

This section discusses technology availability as it relates to the Yukon grid connected scenario. For this scenario, an SMR with an electrical capacity of up to 100 MW is being considered. Based on current installed capacity, ongoing projects, and projected future energy requirements, larger SMRs are not expected to be suitable. New Brunswick (NB) Power has a project underway to deploy the ARC-100 (100 MW) SMR and have it operating by 2030 [46]. This is currently the only 100 MW SMR project underway in Canada and is used as an example when referencing project specific information. Phase 2 of the VDR and the preliminary design is expected to be completed by the end of 2023 [47]. Phase 3, which includes procurement orders, construction permit licensing and approval, site preparation work, and the execution of a construction contract, is scheduled for completion in 2026 [47]. The final phase, deployment, is expected to run from 2027-2030 [47].

Another example that can be used is the deployment of the BWRX-300 at the Ontario Power Generation (OPG) run Darlington Site, where operation of the first unit is expected by 2028 [46]. SaskPower also has a plan to deploy the BWRX-300 SMR in Saskatchewan with its operation commencing as early as 2032 [46]. The BWRX-300 is a 300 MW reactor and is expected to be too large for the Yukon but is relevant in terms of the deployment of a grid-scale SMR. These projects highlight that grid-scale SMRs are progressing rapidly and that there are expected to be multiple grid-scale SMRs operating in Canada within the next decade.

Another important note from a SMR feasibility study conducted by provincial utilities (SaskPower, NB Power, Bruce Power, and Ontario Power Generation) highlights future plans for the domestic supply of these technologies in Canada.

> “Supply chain assessment studies…have shown that between 50 to 60% of the components could be manufactured in New Brunswick, and this figure could be increased with some capability development. Much of the remaining components can be supplied within the rest of Canada. This high percentage is made possible due to the simplicity of design resulting from the inherent safety characteristics of these advanced designs.” – *Feasibility of Small Modular Reactor Deployment and Deployment in Canada* [46]

ARC Canada is planning on opening production facilities in New Brunswick to create a domestic supply chain for the SMR technology. The study also highlights the capabilities of sourcing much of the equipment and necessary components locally, and this is applicable to other SMR designs and vendors. Specific supply chain assessment studies would need to be conducted to evaluate the percentage of components that could be manufactured locally in the Yukon. However, the conclusion remains that the majority of components would be domestically available within Canada.

4.1.2 Remote Off-Grid Mine Site Scenario

This section discusses technology availability as it relates to the remote off-grid mine site scenario. The remote off-grid mine site scenario considers an SMR with an electrical capacity of 25-30 MW, as this is considered to be a good estimate for the energy requirements of a typical mine site. There are currently no SMR designs undergoing the CNSC vendor design review at this electrical capacity per unit, however a nuclear power plant may be comprised of multiple smaller SMRs. The modular feature of SMR's allows for smaller SMR designs in terms of electrical capacity to be scaled up with multiple units to meet the energy demands for this use scenario. The *Feasibility of Small Modular Reactor Deployment in Canada Report* [46] discusses a four-unit commercial deployment (totalling 20 MW) of the MMR by USNC at remote mine sites. Although not exact in terms of electrical capacity, information from this scenario is used as example representative project information.

The Global First Power (GFP) project is currently underway to deploy a 5 MW MMR at the Chalk River Site with expected operation by 2027 and an operational life of 20 years. The deployment of the first unit would demonstrate licencing and commercial operation and would provide experience to facilitate the deployment of additional units at other locations.

The MMR demonstration unit will be the first commercial SMR project completed in Canada. This demonstration project is crucial to proving the efficiency and effectiveness of SMRs and will streamline the current and future deployment process for more SMRs.

4.1.3 Microgrid Community Scenario

This section discusses technology availability as it relates to the microgrid community scenario. This scenario considers an SMR with an electrical capacity of 1-5 MW based off the current electrical capacities of the Yukon's microgrid communities. As discussed in Section 4.1.2, the GFP project is underway to deploy a 5 MW MMR at the Chalk River Site. Bruce Power and the Nuclear Innovation Institute have also been exploring opportunities with the 1-5 MW eVinci micro reactor from Westinghouse Canada for use in remote communities. These projects and designs are used as examples when referencing project specific information for this use scenario.

As discussed above, the single unit MMR deployment at the Chalk River Site is expected to be operating by 2027. This demonstration unit will demonstrate the effectiveness of an SMR to power a microgrid in remote locations.

The eVinci microreactor is currently in the application process with the CNSC to begin its pre-licensing VDR. There are no projects underway to deploy an eVinci microreactor in Canada, however, Bruce Power has partnered with Westinghouse to advance application of the eVinci technology to support Canada's net zero initiative [48]. Recent studies have concluded that the reactor can provide clean and cost-competitive energy to decentralized, off-grid markets in Canada [49]. It was concluded that a single eVinci reactor is expected to be between 14% to 44%

cheaper than a diesel generator, with estimated costs just below $300/MWh [50]. Although no current project is underway, as the VDR progresses for the eVinci, it can be assumed that the technology will be deployed in the coming years.

4.2 Logistical Considerations

This section assesses logistic supply chain considerations that apply to the construction and operation phases of potential SMR projects in the Yukon. Logistical considerations relevant to the deployment of SMRs in the Yukon include transportation to remote areas, the availability of equipment and specialists that are needed during the operational phase, the local labour force or industry requirements for the construction and operation of SMR projects and required industrial infrastructure.

4.2.1 Yukon Grid Connected Scenario

This section discusses the logistical considerations of deploying an SMR to power the YIS, the main Yukon grid.

The deployment of an SMR would create many jobs and require a significant number of personnel for all phases of the project. Given that no SMR projects have reached the construction or site preparation phases yet in Canada, there is no direct operational experience on staffing requirements. The staffing requirements associated with a single grid-sized demonstration unit built in Ontario have been estimated in the Canada SMR Feasibility study, based on the 300 MW BWRX-300 Darlington New Nuclear Project [46]. Average annual job estimates for the construction and operation of the first demonstration unit include 684 jobs during project development, 1604 jobs during manufacturing and construction, 210 jobs during operations, and 163 jobs during decommissioning. These estimates include direct, indirect, and induced jobs created from the project, and are not solely reduced to job or staffing requirements for working at the plant. Job estimates are less for a smaller 100 MW SMR deployment, but this is considered as a representative and bounding case.

The requirement of personnel with specialized skills and trades necessary to construct and operate an SMR poses a challenge for the Yukon. Most of the construction for an SMR is done at the applicable vendor’s manufacturing facility, before the SMR is transported and installed at the site. However, engineering, and nuclear technicians on site are still required. SMRs have smaller workforce requirements than larger conventional nuclear reactors. However, specialized staff such as nuclear operators would need to be trained to contribute to this workforce given that there is no current nuclear industry in the Yukon.

The main Yukon grid, and the communities it powers, are accessible by both road and air from the rest of Canada. Although the transportation of equipment would be over long distances, especially by road, the transportation of the SMR to power the Yukon grid is feasible. Larger components can be transported by truck, while smaller equipment can also be flown in. Canada is a leading country in the innovation and deployment of SMRs and new nuclear technologies, and the availability of equipment and technologies within Canada is discussed in Section 4.1.

An advantage of SMRs is their long refueling cycle. The ARC-100 reactor has a 20-year refueling cycle and 60-year operational life [44]. Therefore, after the initial installation of the SMR, the fuel will only need to be replaced twice during its lifetime of 60 years. This refueling cycle is similar in many different SMR designs that have higher electrical capacities.

4.2.2 Remote Off-Grid Mine Site Scenario

This section discusses the logistical considerations of deploying an SMR to power a remote off-grid mine site in the Yukon.

Staffing requirements vary greatly depending on the electrical capacity of the reactor and plant. The *Economics and Finance WG Report - SMR Roadmap* [21] provided additional estimates for the staffing levels required for SMRs. For a conventional 1000 MWe nuclear power plant, the International Atomic Energy Agency (IAEA) assumes 1 staff member per MWe installed capacity [21]. SMRs are designed to minimize staffing requirements as compared to conventional reactors. For example, NuScale claims that a 600 MWe NuScale facility can be staffed with 365 employees, or about 0.6 employees per MWe [21]. The minimum staffing requirement is assumed to be 20 people, regardless of reactor size [21]. A 2016 Hatch study estimated a minimal security requirement of 10 personnel, plus 6 or 10 operators and support staff for 3 MW and 10 MW plants respectively [21]. A 20 MW four-unit MMR plant can be assumed to have staffing levels that are much lower than the grid-connected scenario.

Remote off-grid mine sites that are accessible by road from the rest of the Yukon are feasible for the transportation of the SMR and all required equipment. Larger equipment can be transported by truck while smaller items can be flown in. Any equipment flown into Whitehorse and the surrounding communities will still require transport by road to arrive at mine sites, and any equipment travelling by road from somewhere else in Canada will have a longer transportation distance than for the grid connected scenario.

It is expected that most planned and future mine sites will have some form of access road connecting the site to the rest of the Yukon. For example, the proposed Casino mine will include the construction of an access road, a 120 km road connecting the mine to the existing Freegold Road [51]. USNC states that the MMR can be easily transported by ship, rail, and road, but air transportation is not discussed [38]. This is similar to the eVinci microreactor in which it can be transported using standard transportation methods, but it is not specified whether it can be transported by air [45]. Currently, it can be assumed that SMR deployment is only feasible if the mine sites are accessible by road. The small size of the reactors being considered makes them suitable for remote locations due to this ability to be transported by standard transportation methods.

The MMR reactor considered for the four-unit 20 MW plant has a 20-year operational life and no refueling will be required during this time. Therefore, the reactor comes assembled with its fuel and will operate, without refueling, until the end of its life. An SMR with a lower operating life can be ideal for remote mines, depending upon the expected life of the mine.

4.2.3 Microgrid Community Scenario

This section discusses the logistical considerations for deploying an SMR to power the communities in the Yukon that are isolated from the main Yukon grid.

As discussed in Section 2.2.6.3, there are 5 communities in the Yukon that are isolated from the YIS and are powered by their own microgrids. The community of Old Crow is the most isolated from the rest of the Yukon and is only accessible by air, apart from years when a temporary winter road is constructed to support big projects. When there is a winter road connecting Eagle Plains to Old Crow, it is approximately 280 km long and is a 12-hour trip by truck and only open in winter months for a few weeks at a time [52]. This road is not built annually, and the two most recent roads were constructed in 2014 and 2022, as the construction of the road itself is a large construction project. Travelling to these remote communities poses additional challenges that need to be considered. Extreme weather, potential impacts of permafrost thawing, and other hazards need to be assessed before this transportation to remote communities, especially over long distances, could occur. The transportation challenges for these communities may be seen as a benefit for SMRs as compared to other energy sources, considering that they do not require frequent transportation of fuel or resources. While transportation to remote sites is a challenge, applicable SMRs are designed to be transported by standard methods and this is not expected to be a barrier.

The length of the refueling cycle will also be important for these remote communities and the necessary personnel. As previously mentioned, an MMR reactor would have an operational life of 20 years and require no refueling during this time. The eVinci reactor has 3+ years of full power operation before refueling is required [45].

Another challenge for remote communities is having sufficient personnel to install and operate SMRs due to the small populations of these communities. Although no exact estimates for personnel are given, the MMR reactor has an installation time within ‘months’ and the eVinci micro-reactor has a target for installation time that is less than 30 days [38, 45]. The eVinci reactor would be fully built, fueled, and assembled prior to transportation to a remote community. It can be concluded that the personnel required for these small reactors will be less than those required for the Yukon grid connected and remote mine site scenarios. However, the minimum estimate of 20 personnel noted in Section 4.2.2 is relevant to operation of SMR reactors with small electrical capacities like those considered for this use scenario and will require further consideration in terms of staffing and training.

4.3 Fuel Availability and Management

This section assesses the robustness of the fuel supply chain, the interim storage of spent fuel or other high level radioactive waste, and other waste management concerns.

The availability of the fuel required for SMRs to operate is an important consideration. The supply chain of the fuel for specific reactor technologies that are used as examples for each use scenario are discussed within their respective sub-sections. Although many modern fuels are modified further, many consist of High-Assay Low-Enriched Uranium (HALEU) fuel. This is a uranium-based fuel where the percent composition of uranium-235 (U-235) has been enriched between 5% and 20% through the process of isotope separation [53]. Currently, there is no domestic supply chain for this enriched fuel. Historically, Canada and the USA have relied on Russia or other foreign suppliers for most of the fuel used to power their nuclear reactors [53]. The invasion in Ukraine has frozen any imports of enriched uranium from Russia.

This has emphasized the need for a domestic supply chain for HALEU fuel, and the United States congress has taken steps to facilitate funding towards the licensing of production facilities and establishment of a HALEU stockpile [54]. Short term solutions are also being considered, as it will be years until a domestic supply chain can produce HALEU at commercial levels to sustain rising levels of nuclear operation in North America [54]. While these concerns are noted, they are not expected to represent a barrier to SMR deployment in the Yukon given the timelines being considered. It is assumed that potential SMR deployment in the Yukon would occur after the completion and operation of current SMR projects underway in Canada, allowing time for the development of a domestic supply chain.

It is also worth noting that Saskatchewan has the richest deposits of uranium in the world. The opportunity is arising for Saskatchewan to be a world leader in the supply of uranium to power advanced nuclear reactors globally and is noted in the *Feasibility of Small Modular Reactor Deployment in Canada* Report that SaskPower was involved in producing [46], although enrichment services would need to be imported. There are no current plans in Canada to develop the necessary fuel fabrication facilities for enrichment to happen domestically.

An important consideration for fuel and waste management is the long-term storage of nuclear waste. Currently, the plan in Canada is to construct a deep geological repository to safely contain and isolate Canada's used nuclear fuel. A deep geological repository is a series of underground tunnels and placement rooms constructed at a depth of more than 500 m [55]. The NWMO is responsible for the safe long-term management of nuclear fuel in Canada, including waste created from new or emerging technologies such as SMRs. Currently, the NWMO is in the process of site selection, with two potential options that safety reports have confirmed are both suitable [55]. Both sites are within the province of Ontario. The site selection is expected to be completed in 2023, which will be followed by an approximate 10-year regulatory and licensing process [55]. Overall, it is assumed that any waste generated from SMRs deployed in the Yukon would be managed by the NWMO and deposited in a deep geological repository located in Ontario. NWMO is responsible for the transportation of spent fuel from the Yukon to the repository site. No nuclear waste would be stored long-term within the Yukon.

Prior to the transportation of spent fuel to the repository, the interim storage of spent fuel will need to be discussed with the applicable SMR design vendor. Spent fuel can be stored on site until the NWMO is able to transport it to the repository. If this is not desired, the Yukon can discuss and negotiate with the SMR vendor to have the storage of spent fuel take place at an interim facility.

4.3.1 Yukon Grid Connected Scenario

This section discusses fuel availability and related considerations for the deployment of an SMR to power the main Yukon grid.

The ARC-100 reactor uses 13.1% enriched HALEU fuel [56]. As discussed in Section 4.3, a domestic supply chain for HALEU fuel in the U.S. is being developed and should be operating commercially in the coming years. This is backed up with the following statement included in the SMR feasibility study produced by provincial utilities:

> "ARC Clean Energy is working with fuel suppliers to ensure a secure supply of HALEU and with Canadian fuel manufacturers for the manufacture of the metallic fuel bundle assemblies for the first unit. It should be noted that several different reactor designs use HALEU fuel and it is a priority of the US Department of Energy to assist fuel suppliers establish this capability. Further, conceptual work is occurring regarding a reconstitution facility to allow the reuse of the ARC-100 fuel as well as the ability to deal with used CANDU fuel. Given the 20-year fuel cycle, this facility is not required for the first unit." – *Feasibility of Small Modular Reactor Deployment and Deployment in Canada* [46].

Long term waste from the ARC-100 would be significantly reduced as it is capable of consuming and recycling its own waste. Since it also has a very long refueling cycle of 20 years, any changes in the short-term supply of fuel would not have a significant impact on operations. As with most SMR designs, spent fuel and other radioactive waste would be sealed and sent to a geological repository. Spent fuel is typically not stored on site.

4.3.2 Remote Off-Grid Mine Site Scenario

This section discusses the fuel availability and related considerations for the deployment of an SMR to power remote off-grid mine sites in the Yukon.

The MMR uses low-enriched uranium, manufactured as Fully Ceramic Micro-encapsulated (FCM) TRISO fuel. This fuel consists of spherical particles of uranium with ceramic layers that promote inherent safety and is commonly used with other SMR designs. A TRISO-x Fuel Fabrication Facility is being developed in Tennessee and has received support from the U.S. Department of Energy [57]. Site preparation and construction is beginning this year and the expected start-up of the facility is as early as 2025. This provides a source of the TRISO fuel needed for the MMR, and other SMR designs. It is worth noting that the MMR reactor would come fully fueled when installed and would not require refueling during its operational life. It is noted that the same HALEU supply chain considerations discussed in Section 4.3.1 would apply.

Different SMR designs are very similar in terms of spent fuel storage and waste management. The MMR produces 2 metric tons (1 m^3 [38]) of radioactive spent fuel over its operational life in a confined and solid form and is sealed in a spent fuel casket [38]. The spent fuel casket can then be sent to and stored in a geological repository. There are also opportunities for spent fuel to be recycled and used again by newer SMR technologies, greatly reducing the amount of long-term waste.

4.3.3 Microgrid Community Scenario

This section discusses fuel availability and related considerations for the deployment of an SMR to power remote communities in the Yukon.

The MMR fuel availability and spent fuel considerations are discussed above in Section 4.3.2. The eVinci uses the TRISO fuel design similar to the MMR at a different U-235 enrichment [56]. Fuel supply chain considerations would therefore be similar for the eVinci as the MMR discussed in Section 4.3.2.

The eVinci would operate in similar ways to the MMR reactor, where there is no long-term spent fuel or waste storage on site. Each refueling cycle, the spent fuel in its sealed cask can be transported to a geological repository or sent to be recycled.

4.4 Benefits

This section discusses the benefits from the deployment of an SMR in the Yukon. Benefits as they relate to cost and a comparison with other energy options are covered in Section 4.4.

4.4.1 GHG Emissions

The ability of SMRs to provide a clean source of energy for heating and electricity is a major benefit of the technology. Furthermore, they were recently designated as a clean energy technology eligible for up to a 30% investment tax credit by the Government of Canada [5]. Section 2.2.2 discussed the current emission reduction targets for the Yukon. As noted, the Yukon set a goal in 2020 of reducing GHG emissions by 30% of 2010 levels by 2030. In 2021, the Government of Yukon updated this goal to a 45% emission reduction to further emphasize the urgency of the climate crisis. The Government of Yukon has current plans in place to help to meet this target, however, they are only expected to reduce emissions in 2030 to two thirds of the 45% reduction target. Further action is needed to help meet this goal. It is also important to consider Canada's net zero commitment by 2050, and the projected increasing energy demands in the Yukon that are highlighted in Figure 4.

The Yukon had a total energy capacity of 156.6 MW in 2017 [15]. Of this 156.6 MW, 62.7 MW is supplied by diesel or LNG [15]. This electrical capacity includes current supply to mines and microgrid communities. Section 2.2.2 discussed the *10 Year Renewable Electricity Plan* from the YEC, which outlined planned energy renewable projects to generate at least 93% of energy for the main grid from renewable sources [14]. The long-term energy generation profile in this report projects that 97% of energy supplied to the main grid will be supplied from renewable sources by 2030 [14]. As a result, SMR deployment to the grid would not have a significant impact in terms of reducing GHG emissions in the near term. If capacity requirements continue to increase into the future, SMRs can be seen as a viable option to maintain clean energy requirements and the net-zero target. For GHG emission reduction, greater benefits can be seen for the off-grid mine site and microgrid community scenarios.

The mining sector is a significant contributor to the Yukon's GHG emissions, with mining accounting for 8% of total emissions in 2019 [8]. However, GHG emissions from mining vary by the ongoing mining operations in the Yukon. From 2009 to 2017, mines contributed to 10-15% of total emissions [1]. SMR deployment at mine sites can help to eliminate GHG emissions resulting from diesel generation and significantly reduce emissions from the mining sector. Additionally, SMRs can be deployed to allow for the development of future mines without diesel generation.

Microgrid communities are currently solely powered by diesel, apart from the new solar project in Old Crow that is discussed in Section 2.2.6.3. As of 2017, microgrid communities accounted for a total electrical capacity of 7.5 MW [15].This capacity can be largely replaced by clean electricity from SMRs.

Since electricity generation and mining only accounts for 15% of the total 2019 emissions, further sectors need to move towards clean energy to meet future targets and eventually reach net-zero. In 2019, on-road gasoline and on-road diesel accounted for a combined 56% of total GHG emissions, and heating accounted for 16% [8]. These sectors can also be made green through the deployment of SMRs. SMRs have a thermal capacity where this energy can be used towards district or industrial heating. The transportation industry is more difficult as electric vehicle use is currently very scarce in the Yukon. However, as electric vehicle use increases, SMRs can provide the electricity required to charge these vehicles. Heating and transportation benefits are further discussed in Section 4.4.5.

It is also important to consider future population growth and the resulting increase in electricity requirements that will be seen moving forward. From 2016 to 2021, the Yukon experienced the largest population growth by percentage compared to all provinces and territories in Canada at 12.1%, reaching a population of 40,232 in 2021 [58]. The Yukon Bureau of Statistics is anticipating a population of 49,040 by 2030 with an average annual growth rate of around 1.6%, and 55,570 by 2040 [59]. As the population continues to grow, energy demand and requirements will continue to increase. SMRs have a strong case for helping to meet future energy demands, given that the Yukon already has renewable energy projects underway and that the deployment of SMRs in the Yukon is not expected to occur until after current planned SMR projects in Canada are well underway.

4.4.2 Land Use

4.4.2.1 Size

The size of the nuclear power plant site for SMRs is minimal compared to other energy options. Alternative energy options such as solar, wind, and hydro require a very large amount of acreage. In the United States, on average wind turbines require 0.75 acres per MW of electrical capacity [60]. A solar power plant requires between 5 and 10 acres per MW of electrical capacity [61]. The geography of hydropower plants can greatly vary, however, an average across the US is 0.265 acres per MW of electricity [62]. It is also important to consider that hydro is more site dependent and requires a flowing body of water with an elevation drop to produce energy. These options are also very visible from far distances, specifically for hydro and wind.

It can be assumed that SMR designs with similar electrical capacities will require a similar amount of space. However, the land required will be dependent on the type of reactor and vendor that is chosen. For the Yukon grid connected scenario, the total plant size of the ARC-100 SMR is less than a city block [44]. The SMR-160 (160 MWe) from Holtec International, with a larger electrical output than the ARC-100, takes up less than 5 acres of land for a single unit deployment [40]. Given that a “city block” is not a definitive amount of area, an area of 5 acres is used as a conservative estimate for the land required for the ARC-100 reactor. With this assumption, the total Yukon grid could be powered with a nuclear power plant 5 acres in size. For comparison, wind, solar, and hydro, would each require 75 acres, 500-1000 acres, and 26.5 acres, respectively for the same energy requirement of 100 MW. Further infrastructure for energy storage would also be required to address the intermittency of solar and wind and may not adequately counter seasonal effects (e.g., lack of sunlight during winter months).

For the remote off-grid mine site scenario, a standard two-unit MMR plant is less than 5 acres in size [38]. For four-units, it is conservatively assumed that the total plant would be less than 10 acres in size. For comparison to wind, solar, and hydro for the same energy requirements, they would each require 15 acres, 100-200 acres, and 5.3 acres, respectively.

For the microgrid community scenario, since a two-unit MMR plant requires less than 5 acres, it is assumed that a single unit would require less space. Although there is no specific acreage estimate from Westinghouse given for the eVinci, it is assumed to either be similar to the MMR or even less in terms of space required. For comparison, wind, solar, and hydro for the same energy requirements, would each require 3.75 acres, 25-50 acres, and 1.325 acres, respectively.

4.4.2.2 Disruption

Another important land use consideration is the disruption on nature and traditional territories caused by the energy project. This was noted as a concern for new hydro-electric projects in the Yukon in the *Small Modular Reactors in the Yukon Engagement Report* [63]. There is limited interest in new hydro-electric projects due to landscape effects such as the flooding of traditional territories. The limited land use required for SMR deployment and lack of disrupting river ecosystems would avoid this concern. Additional concerns from this report are discussed in Section 4.7.

4.4.2.3 Siting Characteristics

Determining the site for a nuclear plant involves a site evaluation process in accordance with *RD-346: Site Evaluation for New Nuclear Power Plants* [64]. This regulatory document involves many criteria that must be considered when evaluating a site, including an evaluation against safety goals, consideration of natural and human-induced factors, evaluation of external hazards such as seismic events, biodiversity of the site and possible impact on the environment, and population and emergency planning considerations. When determining a site for SMR deployment in the Yukon, these factors need to be considered and this site evaluation must occur.

Proximity to a water body (river or lake) for cooling water is another important consideration. Nuclear reactors with a thermal capacity greater than 25 MWth will require access to cooling water. Therefore, an SMR connected to the Yukon grid would need to be located close to a water body, while the eVinci and MMR reactor for off-grid mine sites and microgrid communities would not.

In order to enhance emergency preparedness and risk management measures, all nuclear plants have a defined exclusion zone surrounding the reactor building where no one permanently resides. Radiation protection regulations have established a maximum effective dose of 1 mSv/year to members of the public and therefore, anyone living at the boundary of the exclusion zone can not exceed this amount. This is another important factor, as the site chosen for the plant must be situated away from nearby populated areas. Historically, Canadian nuclear power plant exclusion zones have had a conservative size of 914 m radially from the reactor building [65]. Though still largely estimated, the exclusion zone for SMRs is anticipated to be much smaller than those for older conventional nuclear power plants [66]. This area is also dependent on the type and size of the reactor that is chosen. Smaller reactors such as the MMR and eVinci, with their many inherent safety features, would have a very minimal exclusion zone, if any at all.

4.4.3 Economic Development

The deployment of SMRs can have a positive impact on a local economy through the creation of jobs related to the SMR project, as well as the possible local production of equipment and resources. Job estimates for each use scenario are provided in the sub-sections of Section 4.2. As noted in Section 4.1.1, ARC Canada is planning on opening production facilities in New Brunswick for the local production of SMR equipment and resources. With any SMR vendor, there is the possibility of locally sourcing equipment, where possible. This creates a domestic supply chain, additional jobs, and economic growth.

Currently, there is no available information to understand the extent of local development can occur in the Yukon from SMR deployment. Detailed studies for local economic development with the applicable SMR vendor would need to be completed in the future. The SMR feasibility study provided general estimates of the economic benefits that come with a possible SMR deployment.

For example, the SMR Feasibility Study [46] concluded that a four-unit MMR mine site deployment in Ontario would have the following economic impact in the Province:

- Employment on an annual average basis of 221 jobs during project development, 525 jobs during manufacturing and construction, 199 jobs during operations and 154 jobs during decommissioning
- Impact on GDP (direct, indirect, and induced) of over $659 million
- Increase in provincial revenues of $235 million

These estimates conclude the positive impacts that an SMR project would have on provincial revenues, GDP, and job production. Although they are specific to a 20 MW four-unit MMR deployment, any SMR project is expected to have similar positive economic impacts.

4.4.4 Energy Security and Dependability

A significant advantage of SMRs is constant and reliable energy production. Whether connected to the grid or starting up from a completely de-energized state, once an SMR is running there can be confidence that there will be a consistent energy supply until refueling is required. SMRs can act alone as a base load, with load following capabilities to match fluctuating energy demands. However, they can also be used alongside diesel or renewable energy sources, which can be used for peak shaving. For example, there can be an SMR operating at a constant 5 MW electrical capacity, and at times of peak demand, diesel or other options can be used in conjunction to meet these peak demands.

In the Yukon, diesel is primarily used for remote off-grid mine sites and for microgrid communities. The main Yukon grid utilizes renewables such as hydro, and has some capacity coming from diesel and LNG. Diesel and LNG need to be imported into the Yukon, and for remote mines or communities, diesel needs to be transported over long distances by truck or air. The remote community of Old Crow needs to fly in all its diesel. Energy supply has therefore been dependent upon this transportation of fuel. Conditions such as weather storms or other external hazards can impact this transportation of fuel. Snowstorms can create challenges for the transportation of fuel.

SMRs eliminate the need for frequently transporting fuel since refueling occurs after a certain number of years, depending on the SMR design. Additional fuel bundles can be stored on site and the refueling of an SMR can be staggered to allow them to stay online for the entirety of their operational life [67]. SMRs reduce the dependency on transportation of fuel and provide constant energy through autonomous operation regardless of external conditions.

4.4.5 Industrial Development and District Heating

Along with the use of SMRs to power the grid and provide clean electricity, they can also be used to provide a clean source of heat. For residential and commercial sectors, only 26 percent of Yukon's heating energy currently comes from renewable sources, and heating accounted for 22% of Yukon's greenhouse gas emissions in 2016 [15]. In 2020, considering all sectors, heating accounted for 18% of total emissions [68]. Carbon free production of heat is crucial to meeting Yukon's carbon free energy goals and a net-zero future.

Although the production of heat from nuclear plants is not new, SMRs due to their smaller size, provide quantities of heat that are more compatible with the heating requirements for district heating. The ARC-100 has a thermal capacity of 286 MW, the MMR has a thermal capacity of 15 MW per unit, and the eVinci microreactor has a thermal capacity of 13 MW per unit. This energy can be used for district heating to heat the homes or living quarters of Yukon residents, regardless of the use scenario. The heat can also be used for industrial purposes to help promote industrial development with a carbon free heat source, or to heat greenhouses to grow produce.

4.5 Cost and Competitiveness with other Electricity Sources

This section provides an economic analysis of the cost of generation over the life of the project. The cost comparison will include comparison to other electricity sources, such as existing fossil fuel plants, and renewable sources. Grid costs are developed drawing from recent studies on the impact of connecting 2-10 MW generators in the various regions throughout the Yukon (Dawson City, Mayo, Haines Junction, Whitehorse, and south of Whitehorse).

The two primary data sources for the economic analysis are:

- 2020 Economics and Finance Working Group - SMR Roadmap [21]
- Navius 'Meeting the Yukon's electricity needs through 2050" Aug 2022 [69]

Other sources are listed in the table footnotes.

4.5.1 Compared Generation Technologies

The following electricity generation technologies/types are covered in this study to compare the cost and competitiveness of SMRs:

1. **SMR** – Project options with a 20-year lifespan for the off-grid and mine site scenarios and a 40-year lifespan for the on-grid scenario.
2. **Diesel** – Modular diesel generator sets at 2 MW per genset and deployed as a baseload asset (i.e., 80% capacity factor)
3. **Diesel + Wind Offset** – Modular diesel generator sets at 2 MW per genset and deployed as a baseload asset (i.e., 80% capacity factor) but with associated wind turbine generators matching the same installed capacity to offset diesel generation.
4. **Diesel + Solar Offset** – Modular diesel generator sets at 2 MW per genset and deployed as a baseload asset (i.e., 80% capacity factor) but with an associated solar PV facility matching the same installed capacity to offset diesel generation.
5. **Wind + 4h Battery** – Wind turbine generators deployed with a 4-hour battery energy storage system at a matching capacity to firm up the generation profile.
6. **Solar + 4h Battery** – Solar PV facility deployed with a 4-hour battery energy storage system at a matching capacity to firm up the generation profile.
7. **Hydro** – Hydroelectric generator with 60% capacity factor
8. **LNG** – Liquefied natural gas generator sets deployed as a baseload asset (i.e., 80% capacity factor)

4.5.2 Scenarios

The following scenarios are covered in this study to compare the cost and competitiveness of SMRs with other electricity sources when deployed in different applications:

- **SCENARIO 1**: Off Grid Communities [1-5 MW] – Technologies deployed to supply a remote microgrid in Yukon with sizes ranging from 1 to 5 MW (e.g., remote community).
- **SCENARIO 2**: Off Grid Mines [25-30 MW] – Technologies deployed to supply a remote off-grid mine or large industrial facility with sizes ranging from 25 to 30 MW.
- **SCENARIO 3**: Grid Connected [100 MW] - Technologies deployed to supply the Yukon Energy Corporation electricity grid in close proximity to load centres (i.e., large transmission system investments assumed not be included in this study) with the capacity size assumed to be 100 MW.

4.5.3 LCOE Method

The Levelized Cost of Electricity (LCOE), presented in $/MWh, represents in a single value the total capital and operating costs for a generating asset over its expected lifetime. LCOE discounts (using the time value of money) all capital costs, operating costs, and energy output of a given generation asset to their present value equivalents. LCOE is a useful metric for comparing different electricity generation technologies because it allows for direct comparison between heterogeneous generation technologies (e.g. low capital cost/high operating cost generation technologies such as diesel generation, and high capital cost/low operating costs generation technologies such as solar PV generation).

LCOE for each generation technology and scenario is calculated using the LCOE formula as follows:

$$LCOE = \frac{(Overnight\ Capital\ Cost * Capital\ Recovery\ Factor) + Fixed\ O\&M}{Hours\ Per\ Year * Capacity\ Factor} + \frac{(Fuel\ Cost_{HHV} * Heat\ Rate_{HHV})}{1000} + Variable\ O\&M$$

Where each term is summarized as follows:

- **Overnight Capital Cost:** Overnight capital cost, expressed in $/MW, is the initial "all-in" investment per unit of capacity (i.e., cost of the facility) if a generating facility were to be built instantaneously. "All-in" costs include all appropriate indirect costs, overheads, and interest during construction.
- **Capital Recovery Factor (CRF):** The capital recovery factor is a fraction that transforms the overnight capital cost into an equivalent annual payment. The capital recovery factor is calculated as follows:

  $$CRF = \frac{r(1+\mathrm{r})^{\mathrm{n}}}{(1+\mathrm{r})^{\mathrm{n}} - 1}$$

  Where:

  - "r" is equal to the real discount rate.

    $$Real\ Discount\ Rate\ (r) = \frac{1 + Nominal\ Discount\ Rate}{1 + Annual\ Inflation} - 1$$

    The inflation rate is used to convert the discount rate from nominal (measure the dollar value of a product at the time it was produced) to real (prices are adjusted for general price level changes over time).
  - "n" is equal to the lifespan of the asset. The generation technology lifespan represents the usable asset life without having to complete a major rebuild or rehabilitation. In theory, a generation asset could last indefinitely where major overhauls are completed in perpetuity (e.g., if Solar Photovoltaic modules are at end of life after 25 years you could replace all modules and rebuild the entire facility), however, such an endeavour would require a major injection of capital. Therefore, the lifespans assumed for the purposes of this study capture the usable asset life typically found in the industry before major rehabilitation or rebuild is considered.
- **Fixed O&M:** Fixed O&M, expressed in $/MW/year, is the annual expenditure per unit of electricity generation capacity for operations and maintenance, regardless of how much energy is generated (i.e., the amount is fixed and doesn't change with facility usage).
- **Variable O&M**: Variable O&M, expressed in $/MWh, is the expenditure per unit of generation for operations and maintenance.

- **Hours per Year:** The number of hours in a year (i.e., 8,760).
- **Capacity Factor:** Capacity factor, expressed as a percentage between 0% and 100%, is the average annual output (in MW) divided by the installed capacity (in MW). Alternatively (and equivalently), capacity factor is the amount of energy a facility generates in a given year divided by the theoretical maximum if the facility were to output at the installed capacity for every hour of the year.
- **Fuel Cost:** Fuel cost, expressed in $/MMBtu, is the cost of the input fuel required for generation and only applies to thermal generation technologies (as renewable generation technologies have a zero fuel cost).
- **Heat Rate:** Heat rate, expressed in Btu/kWh, is the number of British thermal units required to generate one (1) kilowatt-hour of electricity. In other words, it is the efficiency of a generation technology's conversion from fuel into electrical energy. Heat content of combustible fuels can be expressed in either:
  - Lower Heating Value **–** The theoretical heat adjusted lower to account for the energy required to vaporize the fuel's water content; or
  - Higher Heating Value **–** The theoretical heat excluding any adjustment for the energy required to vaporize the fuel's water content.

4.5.4 LCOE Inputs

Table 9 summarizes technical inputs, like lifespans, capital recover factors, capacity factors, heat rates and marginal emissions that are assumed for each generation technology covered in this study.

All technical inputs are important, but the capacity factor requires additional attention because it can vary drastically depending on the facility's application and type of operation. Capacity factor is occasionally confused with the concept of availability factor. The availability factor captures a facility's up-time or availability to generate electricity. For example, a hydroelectric facility may have an availability factor of 98% (available to generate 98% of all hours), but a capacity factor of 40% (as there is not enough water (i.e., fuel) to generate at maximum capacity for all available hours).

In addition, thermal generation technologies are considered dispatchable when the operator chooses at what capacity output to run the facility (effectively selecting a capacity factor). As a result, "baseload" generation technologies such as hydro and nuclear have high capacity factors and "peaking" thermal generation technologies such as diesel have low capacity factors because they play different roles matching overall generation supply to overall electrical demand. Renewable generation technologies differ from dispatchable generation in that renewable facilities typically operate as and when the fuel (e.g., wind) is supplied, therefore the capacity factor is a function of fuel availability.

However, to make this cost competitiveness comparison 'apples-to-apples', it is assumed that the diesel and LNG options are operating at 80% capacity factor to reflect the same capacity factor as that of a typical SMR. Because LNG and SMR options have a higher upfront cost over operating cost ratio than diesel (i.e., diesel has a lower upfront cost to operating cost ratio), having a higher capacity factor will make the analysis favour LNG and SMR over diesel.

Table 9: Technical Inputs Assumed for Each Generation Technology

	Project Lifespan (years)	CRF (%)	Capacity Factor (%)	Heat Rate (Btu/kWh)	Marginal Emissions (kg CO_2/MWh)	Average Emissions (kg CO_2/MWh)
SMR-40yr	40 Yrs	5.68%[A]	80%	6,200[B]	0 kg	0 kg
SMR-20yr	20 Yrs	7.90%[A]	80%	6,200[B]	0 kg	0 kg
Diesel	20 Yrs	7.90%[A]	80%	9,040[B]	705 kg[C]	705 kg[C]
Diesel + Wind Offset	20 Yrs	7.90%[A]	80%	9,040[B]	705 kg[C]	352 kg[C]
Diesel + Solar Offset	20 Yrs	7.90%[A]	80%	9,040[B]	705 kg[C]	564 kg[C]
Wind + 4h Battery	20 Yrs	7.90%[A]	40%		0 kg	0 kg
Solar + 4h Battery	25 Yrs	6.97%[A]	16%		0 kg	0 kg
Hydro	50 Yrs	5.33%[A]	60%		0 kg	0 kg
LNG	20 Yrs	7.90%[A]	80%	8,259[B]	438 kg[C]	438 kg[C]

***Note A**: Yukon Energy Corp. "10-Year Renewable Electricity Plan Technical Report" Dec 2020* [14]
***Note B**: 2020 Economics and Finance Working Group - SMR Roadmap, PDF p. 72* [21]
***Note C**: Midgard Consulting Estimate. Diesel + renewable offset technology is pro-rated using relative capacity factors for diesel (80%), wind (40%) and PV (16%).*

Table 10 summarizes the overnight capital cost, fixed O&M costs, variable O&M costs, and fuel costs that are assumed for each generation technology covered in this study. All cost data has been converted to 2022 Canadian dollars using appropriate escalation and exchange rates when required.

Table 10: Cost Inputs Assumed for Each Generation Technology

	Overnight Capital Cost ($/MW)			Fixed O&M ($/MW-Yr)	Variable O&M ($/MWh)	Fuel Cost ($/MMBTU)		
	Off Grid Communities [1-5 MW]	Off Grid Mines [25-30 MW]	Grid Connected [100 MW]	All Scenarios	All Scenarios	Off Grid Communities [1-5 MW]	Off Grid Mines [25-30 MW]	Grid Connected [100 MW]
SMR-40yr			$11.0 M [A]	$0.30 M [A]				$1 [B]
SMR-20yr	$12.7 M [A]	$12.7 M [A]		$0.30 M [A]		$1 [B C]	$1 [B C]	
Diesel	$3.5 M [E]	$2.2 M [E]	$2.2 M [E]	$0.08 M [E]	$19 [E]	$38 [D C]	$38 [D C]	$33 [D]
Diesel + Wind Offset	$10.0 M [E I]	$6.9 M [E I]	$5.5 M [E I]	$0.09 M [E]	$19 [E]	$38 [D C]	$38 [D C]	$33 [D]
Diesel + Solar Offset	$6.0 M [E I]	$4.0 M [E I]	$4.0 M [E I]	$0.11 M [E]	$19 [E]	$38 [D C]	$38 [D C]	$33 [D]
Wind + 4h Battery	$8.8 M [E H]	$6.9 M [E H]	$5.5 M [E H]	$0.05 M [E F]				
Solar + 4h Battery	$4.7 M [E H]	$4.0 M [E H]	$4.0 M [E H]	$0.07 M [E F]				
Hydro	$23.2 M [F]	$14.1 M [F]	$14.1 M [F]	$0.33 M [F]	$5 [F]			
LNG		$4.1 M [G]	$4.1 M [G]	$0.06 M [E]	$19 [E]		$27 [D C]	$23 [D]

***Note A**: Economics and Finance Working Group - SMR Roadmap, PDF p. 81 (inflated from 2018 to 2022 at 2%)* [21]

***Note B**: Economics and Finance Working Group - SMR Roadmap, PDF p. 72 (inflated from 2018 to 2022 at 2%)* [21]

***Note C**: + 15% remote adder, see tables below for sensitivity analysis showing LCOE Results with 30% and 45% fuel adders.*

***Note D**: Whitehorse sourced fuel pricing provided by YEC over email (inflated from 2018 to 2022 at 2%)*

***Note E**: Navius 'Meeting the Yukon's electricity needs through 2050" Aug 2022* [69]

***Note F**: YEC "10-Year Renewable Electricity Plan Technical Report" Dec 2020* [14]

***Note G**: Midgard Consulting Yukon Thermal Study 2019*

***Note H**: EIA "AEO2020 Capital Costs" Feb 2020* [70]

***Note I**: Economies of scale curve applied informed by a variety of sources (e.g. EIA, NREL, Lazard and IRENA)*

4.5.5 LCOE Results

Table 11 below presents the LCOE results for each generation technology and for each scenario covered in this Study.

Table 11: LCOE Results

	LCOE ($/MWh)		
	Off Grid Communities [1-5 MW]	Off Grid Mines [25-30 MW]	Grid Connected [100 MW]
SMR-40yr			$138
SMR-20yr	$193	$193	
Diesel	$409	$394	$350
Diesel + Wind Offset	$305	$269	$231
Diesel + Solar Offset	$370	$348	$312
Wind + 4h Battery	$212	$170	$138
Solar + 4h Battery	$286	$251	$251
Hydro	$303	$211	$211
LNG		$295	$266

Some key takeaways from the above LCOE results are as follows:

- Overall, SMRs are the most competitive technology option for all scenarios covered in terms of LCOE. However, these results may change if capacity factors for SMRs and diesel resources are lower than the assumed 80%.
- SMR and renewables both have significant capital costs. While diesel and LNG are less capital intensive, they have ongoing fuel costs.
- The second and third best performing technology is Wind + 4h Battery and Solar + 4h Battery respectively but these resources will not be able to generate the same level of capacity firmness as the other technologies (i.e., SMRs, Diesel and LNG).
- LNG is generally more competitive than diesel given a capacity factor of 80%.

Table 12 and Table 13 below show the LCOE results for off-grid scenarios with fuel adders of 30% and 45%.

Table 12: LCOE Results (30% off-grid fuel adder)

	LCOE ($/MWh)	
	Off Grid Communities [1-5 MW]	Off Grid Mines [25-30 MW]
Diesel	$453	$439
Diesel + Wind Offset	$328	$292
Diesel + Solar Offset	$405	$383
LNG		$324

Table 13: LCOE Results (45% off-grid fuel adder)

	LCOE ($/MWh)	
	Off Grid Communities [1-5 MW]	Off Grid Mines [25-30 MW]
Diesel	$497	$483
Diesel + Wind Offset	$350	$314
Diesel + Solar Offset	$441	$418
LNG		$353

4.6 Regulatory Readiness

4.6.1 Federal Requirements

For nuclear projects in Canada, the CNSC is the primary regulator [71]. The licensing process in Canada, which is described by the CNSC in Regulatory documents REGDOC 1.1.1 to 1.1.5, sets out the requirements and procedures for the licensing application for various stages of planning, constructing, building, and decommissioning a nuclear power plant and the monitoring of results:

- REGDOC-1.1.1, Site Evaluation and Site Preparation for New Reactor Facilities, Version 1.2 [72]
- REGDOC-1.1.2, Licence Application Guide: Guide to Construct a Reactor Facility, Version 2 [73]

- REGDOC-1.1.3, Licence Application Guide: Licence to operate a Nuclear Power Plant [74]
- REGDOC-1.1.4, Licence Application Guide: Licence to Decommission Reactor Facilities (under development) [75]
- REGDOC-1.1.5, Supplemental Information for Small Modular Reactor Proponents [76]

While the CNSC has the primary responsibility for enforcing these REGDOCs, it frequently calls on other federal agencies such as Environment and Climate Change Canada, Natural Resources Canada, and Health Canada to review and monitor proponent submissions.

Responsibility for Environmental Assessments in Canada for nuclear reactor facilities typically comes under the responsibility of the federal Government. This responsibility applies only to the provinces and not to the territories where their own EA Acts apply.

While not applicable to the Yukon, the federal regulatory requirements applicable to provinces is presented for informational purposes. In 2019, Canada introduced a new *Impact Assessment Act (IAA)* [77]. This Act requires mandatory early planning and engagement phases with Indigenous communities. This means early dialogue with Indigenous peoples, provinces, the public, and stakeholders to identify and discuss issues early, leading to better project design. It also mandates a single government agency to lead assessments and coordinate Crown consultations, with Indigenous peoples. The Act also requires mandatory consideration and protection of Indigenous knowledge alongside other sources of evidence in impact assessments. It is considered a move from environmental assessment to impact assessment based on the principle of sustainability.

Under the IAA, federal impact assessments are done on designated projects, which are designated either by regulation or by the Minister of Environment and Climate Change [78]. The Physical Activities Regulations (commonly known as the Project List) [79] is the regulation that designates those projects. It provides clarity and certainty as to which projects are subject to the IAA and is required to properly implement the federal impact assessment process.

If a proposed new nuclear power plant is exempted from the federal environmental assessment under the IAA, it is up to the discretion of the minister, how and under what jurisdiction the environmental assessment should be conducted. The Regulations include the following facilities under the new IAA, 2019:

(a) That activity is located within the licensed boundaries of an existing Class IA nuclear facility and the new reactors have a combined thermal capacity of more than 900 MWth; or
(b) That activity is not located within the licensed boundaries of an existing Class IA nuclear facility and the new reactors have a combined thermal capacity of more than 200 MWth.

In the theoretical application of the IAA regulations within the Yukon, based on the size of reactors being considered for the Yukon, new nuclear power plants considered for off-grid or mine site applications would be exempted from the federal environmental assessment under the IAA, and it would be up to the discretion of the federal Minister of the Environment and Climate Change to determine if an environmental assessment would be required. An on-grid plant in the 100 MWe range may exceed 200 MWth, and therefore may not be exempted from the IAA. Section 5.4 of the Transportation of Dangerous Goods (TDG) Regulations [80] sets out the requirements for the loading and securing of dangerous goods, including class 7 dangerous goods (radioactive materials) to prevent damage to the container or to the means of transport that could lead to an accidental release. Section 8 of the TDG Regulations is relevant to accidental release and accidental release reporting requirements. Transport Canada TDG directorate requires that the parties involved in the transportation of dangerous goods develop an Emergency Response Assistance Plan (ERAP).

In addition to the generating facility, the installation of transmission lines require application and permit from the Canada Energy Regulator [81].

In 2002, Canadian Parliament passed the Nuclear Fuel Waste Act (NFWA) [82]. Under the NFWA, the NWMO is responsible and has a legal obligation for safely managing Canada's used nuclear fuel over the long term. This includes the nuclear used fuels that exist now, as well as those produced in the future.

The SMR Roadmap concluded that there are no major impediments to licensing of SMRs for deployment in Canada [83].

4.6.2 Yukon Requirements

Should the Yukon determine that it wants to take responsibility for requiring an environmental impact assessment, it would be governed by the Yukon Environmental and Socio-economic Assessment Act (YESAA), under the direction of the Yukon Department of Environment, Environmental Protection and Assessment, which performs analysis of environmental impacts and administers permits for regulated activities and substances.

An assessment by the Yukon Environmental and Socio-Economic Assessment Board (YESAB) would be required. YESAB has an important role in the protection of the environmental and social integrity of the Yukon. As an independent arms-length body, its role is to administer the YESAA. YESAB’s process ensures that projects actively consider the significance of adverse environmental and socio-economic effects. Developing capacity within YESAB to support the assessment of nuclear projects would be critical for developing an effective assessment process.

In addition, there are several environmental permits that are required for a facility to operate in the Yukon. These permits are issued under *the Environment Act* and its regulations by the Yukon Department of Environment. Some of these permits include:

- Air Emission Permit,

- Water Licence,
- Land Use Permit,
- Special Waste Permit, and
- Solid Waste or Waste Management Permit.

The complete list of permits required are found in the Permit and Authorization Guide for Yukon Activities [84].

The Yukon Department of Energy, Mines & Resources, Land Management Branch has also set out the policy for commercial and industrial land applications.

4.7 Small Modular Reactors in the Yukon Engagement Report

This section discusses the *Small Modular Reactors in the Yukon Engagement Report's* results and any respective feasibility implications from it.

The *Small Modular Reactors in the Yukon Engagement Report* [63] was completed by Calian as part of the overall feasibility analysis for SMRs in the territory. Targeted focus groups and interviews were undertaken with key informants in the Yukon to gain a better understanding of the public opinion surrounding nuclear power and potential SMR deployment in the Yukon. Individuals were asked about any current energy issues in the territory and the potential opportunities or challenges that SMR deployment in the Yukon could generate. The key informants consisted of 23 individuals, representing the mining sector, First Nations, territorial government, utilities, environmental non-governmental organizations (ENGO), and municipalities.

Significant commonalities in key energy issues were identified. These issues included remote community dependence on diesel, limited grid capacities with high anticipated demand, anticipated increased industrial demand from mining, baseload challenges from increased renewables, limited interest in new hydro-electric generation, and co-management requirements for future energy development.

The major energy issues in the Yukon that were identified in these interviews can adequately be addressed with SMRs. SMRs' ability to address remote community dependence on diesel, increasing supply for mine sites, and increasing baseload have been focal points of this feasibility study. A single 100 MWe SMR could provide a base load of power for the Yukon grid by addressing the concerns of limited grid capabilities and stabilizing baseload challenges from increased renewables. Limited interest in new hydro-electric power indicates that Yukoners could be interested in alternative forms of energy, such as SMRs. Further research and engagement on partnering with First Nations as SMR proponents, in joint ventures and in the co-management of nuclear facilities is necessary. First Nations partnerships could provide a viable pathway for future SMR development in the Yukon.

The main challenges identified for deploying SMRs in the Yukon included potential public bias against the technology and limited nuclear knowledge, nuclear waste disposal, remoteness and emergency service needs, the potential abandonment of SMRs, access to fuel and mining concerns, and the Yukoner “identity” being incongruent with nuclear facilities.

Many of the challenges identified by study participants have been addressed within the feasibility study. Nuclear waste disposal and access to fuel were discussed in Section 4.3. As noted, SMRs do not typically store spent fuel on site, and the long-term storage of nuclear waste in Canada will be in a deep geological repository, with two possible sites in Ontario. No nuclear waste would be stored in the Yukon. The study also concluded in Section 4.3 that access to fuel will not be a barrier, and mining for uranium would not be required within the Yukon. The concern of abandonment has been identified and has been considered explicitly in SMR designs for application for off-grid mine sites and microgrid communities. All SMR designs have inherent safety mechanisms, including automatic shutdown, passive cooling in times of an emergency, and a very small emergency planning zone. Thus, by design, remoteness and emergency service needs are not a technical barrier for the deployment of SMRs in the Yukon. At the end of an SMRs operational life, decommissioning occurs. The facility will be fully deconstructed to the point where radiation protection measures are no longer required. The site is restored to an agreed end-state where the land is ready for some form of re-use. The end-state can be determined with First Nations and the fears of SMR abandonment should not pose a technical barrier.

Participants in the engagement study believe that public perception presents some challenges but evidence from the Engagement Study indicates that it would not be an insurmountable barrier for SMR deployment in the Yukon. Additional engagement to determine public perception towards SMRs across a broader population would be beneficial. Additionally, a public education program on nuclear power and the benefits of SMR technology would assist Yukoners in feeling more comfortable with the technology. From the 23 individuals interviewed, only 3 identified as having little or no knowledge on nuclear power, and 22 respondents were characterized as being supportive of nuclear power. This is likely not representative of the general population, as all participants were knowledgeable on energy systems broadly. In addition, one of the challenges identified was the Yukoner “identity” being incongruent with nuclear facilities. It is expected that the average Yukoner has a different perspective on nuclear facilities than those of the study participants. Education and public perception concerns can be addressed through transparent and continued outreach and engagement activities to help the Yukon population learn more about SMR technology. The SMR Engagement Report and Feasibility Study completed by Calian can support further engagement planning. Information sessions with nuclear experts, surveys, increasing discussions on nuclear energy in curriculum, accessible information on nuclear facilities, focus groups, and presentations open to the public are examples of engagement activities that can be pursued moving forward to help increase education and improve public perception towards nuclear facilities.

It was also mentioned by many participants that the Yukon does not want to be the first adopter of a new technology, but instead a “fast follower.” Demonstrated use cases from proposed SMR projects within Canada will help to improve public opinion and education, as currently operating commercial SMRs can be referenced.

5. KEY FINDINGS FOR SMR VIABILITY IN THE YUKON

This section provides a summary of the key requirements that are needed for the successful deployment of SMRs in the Yukon. Recommendations are made as to the actions that the Yukon should consider to facilitate the development and uptake of SMRs.

The availability of the technology is an important factor considered for the feasibility of SMR deployment in the Yukon. There are currently 12 SMR designs undergoing the VDR process in Canada with the CNSC. There are also multiple projects underway in Canada to have SMRs deployed in New Brunswick, Saskatchewan, and Ontario, with expected operation start dates as early as 2027. These projects will help to demonstrate the technical and economic feasibility of the technology. The Yukon does not want to be the first adopter of a new technology but would support following quickly after other projects have been demonstrated. Therefore, this report recommends that Canadian SMR projects proceed further, with the Yukon preparing to be a “fast follower” once technological readiness is proven.

The completion of these projects will also facilitate further development of the domestic supply chain in Canada and improve understanding of the necessary equipment that can be produced locally. Since timelines are still currently theoretical, these projects will also build confidence in the length of the licensing and construction process for an SMR project. The availability of technology does not pose a barrier for SMR deployment in the Yukon, but it is recommended to allow current Canadian projects to progress in order to provide experience to inform future potential SMR deployment in the Yukon.

Logistical considerations, specifically staffing requirements, transportation, and refueling cycle, were additional factors considered for SMR feasibility in the Yukon. SMR projects are designed to require fewer workers throughout their entire lifecycle as opposed to traditional nuclear plants. However, it is still expected that some specialized staff will need to be trained or relocated, but this is not expected to be a barrier to SMR deployment. It is expected that any potential SMR deployment site will need to be accessible by road. The long refueling cycle for SMRs and limited need for transportation of fuel can be seen as a logistical advantage, specifically for remote communities. These transportation considerations are noted but are not expected to represent a barrier to SMR deployment in the Yukon.

The availability of fuel is another important consideration for SMR feasibility in the Yukon. Waste disposal and mining/fuel concerns were identified in Section 4.7 as a concern from engagement respondents. As discussed, many SMRs require enriched fuel like HALEU, and there are short term concerns for the supply of this fuel. Given ongoing efforts to improve the domestic fuel supply chain, availability of fuel is not expected to be a barrier based on the timelines expected for the Yukon. It is expected that long term waste from SMRs will be managed by the NWMO in a deep geological repository in Ontario. There would be no nuclear waste stored long term in the Yukon.

Numerous benefits from an SMR deployment in the Yukon were highlighted. SMRs are carbon free and can help to reduce GHG emissions. Currently, these benefits would be more notable for remote communities and off grid mine sites due to the currently foreseen capacity needs and 10-year renewable electricity plan in place for the main grid. From 2030 and onward, these benefits will become more notable for the on-grid scenario as energy requirements will continue to increase and electrification of different industries will occur. The minimal amount of land use and disruption required for SMRs are additional benefits. Limited interest in new hydroelectric power due to the disruption of river ecosystems was a noted outcome of public outreach activities as documented in Section 4.7. SMRs address this concern due to the minimal amount of land required and lack of disruption of water bodies when compared to other renewable options. SMRs can also induce economic and industrial development due to job creation, local development of equipment, and their additional uses, such as district and industrial heating. Another major benefit of SMRs is consistent and reliable energy production. External conditions such as extreme weather would not influence energy production, and the long refueling cycle would alleviate concerns with the transportation of fuel during extreme weather events.

SMRs were found to be economically competitive with other energy options. In terms of LCOE, SMRs were found to be the cheapest option over time when compared to the other generation technologies in Section 4.5.1. The capital costs for SMRs are higher initially, with lower fuel costs over time. The cost analysis assumed a capacity factor of 80% and a lower capacity factor could change the results of this analysis. It is important to allow for a high capacity factor when an SMR is deployed. This can be done by ensuring the electrical capacity of the SMR is similar to the energy required for the deployment.

In terms of regulatory readiness, there are no major impediments to the licensing of SMRs for deployment in the Yukon. It is noted in the SMR Roadmap that satisfying impact assessment requirements can be a risk to the cost and schedule of SMR projects [16]. YESAB has never undertaken a nuclear assessment process. YESAB and other agencies may require additional support and personnel in order to undertake the assessment of a nuclear project.

Preliminary outreach studies conducted in 2022 found that 22 of 23 correspondents were characterized as favourable of nuclear power. However, the public perception of nuclear energy in the Yukon presents some challenges, but it would not be an insurmountable barrier for SMR deployment in the Yukon. Many concerns repeated by respondents to the outreach study in the Yukon were addressed in this feasibility study and would not have any impact on their feasibility. Concerns related to bias against nuclear energy and the Yukoner “identity” being incongruent with nuclear power need to be addressed through further education and outreach activities. Information sessions with nuclear experts, surveys, increasing discussions on nuclear energy in curriculum, accessible information on nuclear facilities, focus groups, and presentations open to the public are examples of activities that are recommended to help improve public perceptions of nuclear power and general education on SMRs. The Yukon being a “fast follower” for SMR deployment would help to address these concerns through referencing proven operation of SMR technologies in Canada.

Overall, it is concluded that there are no major barriers preventing SMR deployment in the Yukon. It is recommended to allow further advancement of current SMR projects in Canada over the next several years prior to considering deployment of SMRs in the Yukon. This will allow an improved understanding of infrastructure and logistical feasibility considerations, allow improved development of the domestic SMR supply chain (including fuel), and aligns with the results of public outreach indicating a desire to be "fast followers" rather than first adopters. Additionally, while SMRs are shown to be economically competitive with other sources, deployment situations allowing high capacity factor and a need for higher up-front investment are noted as feasibility requirements. Based on currently anticipated capacity needs and planned projects, remote communities, and off-grid mine sites appear to be the most optimal use cases for realizing the benefits of SMRs in terms of GHG reductions, although this may change in the future as electrification of the transportation sector progresses. Additional engagement to determine public perception towards SMRs across a broader population is recommended, given that the individuals included in outreach to date were knowledgeable on energy systems and may not be representative of the general population. It is recommended to consult with YESAB well in advance of any potential SMR development, given the lack of regulatory experience with SMR projects.

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