Geo-electrical energy feasibility in the North

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Table of Contents

[1. Introduction 1](#_Toc32787321)

[2. Energy Accessibility Challenges in the North 1](#_Toc32787322)

[3. Diesel 2](#_Toc32787323)

[3.1. Current Diesel Import Structure 2](#_Toc32787324)

[3.2. Negative Impacts of Diesel Use 2](#_Toc32787325)

[4. Energy Costs in the North 4](#_Toc32787326)

[5. Alternate Sources of Energy 5](#_Toc32787327)

[5.1. Solar 5](#_Toc32787328)

[5.2. Wind 5](#_Toc32787329)

[5.3. Biomass 6](#_Toc32787330)

[5.4. Hydro 6](#_Toc32787331)

[5.5. Nuclear 6](#_Toc32787332)

[5.6. Geothermal 7](#_Toc32787333)

[6. Geothermal Technology 7](#_Toc32787334)

[6.1. Advantages/Disadvantages 7](#_Toc32787335)

[6.2. Enhanced Geothermal Systems (EGS) 8](#_Toc32787336)

[6.3. Organic Rankine Cycle (ORC) 8](#_Toc32787337)

[6.4. Combining Solar Thermal with Geothermal 8](#_Toc32787338)

[7. Case Studies 10](#_Toc32787339)

[7.1. Fort Liard, Northwest Territories, Canada (Incomplete Project) 10](#_Toc32787340)

[7.2. DEEP, Saskatchewan, Canada (Under Construction) 10](#_Toc32787341)

[7.3. United Downs, Cornwall, UK (Under Construction) 11](#_Toc32787342)

[7.4. Eden Project, Cornwall, UK (Pre-Construction) 12](#_Toc32787343)

[7.5. Otaniemi, Espoo, Finland (Under Construction) 12](#_Toc32787344)

[7.6. Chena Hot Springs, Alaska, USA (Completed) 13](#_Toc32787345)

[8. Cost 14](#_Toc32787346)

[9. Conclusion 15](#_Toc32787347)

[References 17](#_Toc32787348)

# Introduction

Canada, from say 100 km north and east of the USA border,Egmond Associates Ltd (EAL) is looking at the feasibility of using geothermal energy to produce electricity in northern regions where resources are scarce. Northern regions rely on the import of fuel sources from other locations to power their communities. The use of renewable energy sources in northern Canada would allow greater energy-independence for remote, isolated, off-grid communities.

# Energy Accessibility Challenges in the North

In the North, many communities are small, isolated, and lacking in resources. EAL is looking at Nunavut as a primary test case. Nunavut has 25 communities, all of which are isolated from each other, and all of which rely on diesel generators to produces 100% of their electricity [1, p. 2]. These communities are spaced hundreds of kilometers apart, which means connecting the communities together to make a unified grid is unlikely to be viable. A map of Nunavut is shown in Figure 1 for reference.



Figure 1 Map of Nunavut Municipalities

Source: [2]

Shipping diesel to these isolated communities is logistically challenging, requires storage, and is hugely expensive. Deliveries must be made by sea or air. Shipping is only possible for a few months in the summer. If a community runs out in the winter before shipping lanes open, additional fuel needs to be flown in at huge costs.

An alternate power source using local resources could stand to save the communities significant amounts of money, even if the cost of the system is much higher than would be feasible in the rest of the country.

# Diesel

Nunavut is comprised of 25 isolated, coastal communities which rely on imported fuel [1, p. 2]. Nunavut does not produce any of its own fuel sources. The Government of Canada reports that almost 100% of Nunavut’s electricity comes from petroleum products such as diesel fuel [3, p. Table 14]. Although several renewable energy projects have been considered and some are currently under development, renewable energy sources accounted for less than 0.1% of Nunavut’s electricity generation in 2016 [3, p. Table 14]. Despite global awareness of the need to move away from fossil fuels, Nunavut continues to rely on diesel for electricity generation because the fuel is energy-dense and has the ability to be stored [4, p. para. 5]. When compared to other electricity infrastructure, diesel-powered generator facilities are inexpensive to install [4, p. para. 5]. The need to have a fuel source that can be stored in order to produce electricity 24-hours a day regardless of weather conditions is a major factor when considering suitable electricity sources [5, p. para. 3].

The 25 Nunavut communities are spread out over a large amount of land. There is no infrastructure such as roads or electrical gridlines connecting communities [6]. Constructing all-season roads and electrical grids is difficult because of the large distances between communities [6], the cold climate, and permafrost which makes ground infrastructure more challenging and expensive to build. For these reasons, Nunavut communities have remained off-grid.

# Current Diesel Import Structure

The Petroleum Products Division (PPD) [7] and the Qulliq Energy Corporation (QEC) [1], both subsidiary corporations of the Government of Nunavut, oversee the supply of fuel and electricity, respectively, to Nunavut communities. There are complex logistics involved in transporting fuel to Nunavut and supplying communities with electricity.

The QEC, which is the only electrical utility company in the territory, is responsible for forecasting the electricity demands for each of the 25 communities [8, pp. 2-1]. The forecasted electricity demand and diesel generator efficiency is then used to determine the amount of diesel that must be supplied to each community for the coming year.

The PPD is responsible for all fuel imports into Nunavut. The Government of Nunavut (GN) orders that the sale of diesel in the territory through the PPD must be revenue neutral (any surplus or deficit in funding must be balanced over the course of a few years) [7, p. iii].

The PPD orders the diesel based on the forecasted amount calculated by the QEC. All of the fuel is ordered at one time, securing a once-a-year fixed price for the diesel [7, p. 6]. Shipping barges are commonly used to transport the fuel as all Nunavut communities are coastal. Fuel shipments occur during the summer months [7, p. 1] when the sea ice has broken up and water conditions are safer for travel. The shipment of diesel must be enough to last the community for the entire year. Each community has its own fuel storage facility and a diesel generator power plant to produce enough electricity for the community [4].

Sea ice can make shipping difficult and, in some cases, prevent the fuel from reaching the community. If fuel cannot be transported by ship, it must be flown into the communities at great expense [9, p. para. 6]. Otherwise, the community would run out of diesel, and therefore have no electricity or fuel for heating during the year.

# Negative Impacts of Diesel Use

The use of diesel for electricity generation relegates Nunavut to being energy-dependent on an imported fuel source which is difficult to transport into the communities. Additionally, the use of diesel is associated with environmental, health, and safety implications.

There is no safe and economic method to transport diesel to the territories. A report by J. Thomson estimates that between 1970 and 2019, over 9.1 million litres of diesel transported to the Northwest Territories and Nunavut were lost due to truck, ship, and storage tank spills or leakage [9, p. para. 32]. However, lack of consistent and sufficient spill reporting means the actual number of spills across Canada is likely to be much higher than recorded [10]. Oil spillage results in negative impacts on the environment including water contamination and habitat loss [11, p. 1], but also financial losses due to product loss and remediation work. Spills also decrease the amount of fuel received by the community. Hunting is integral to northern Indigenous cultures, and spills which lead to contamination threaten the ability to maintain this tradition [11, p. 1].

The environmental impact of diesel and other oil spills is serious. Diesel evaporates into the atmosphere more rapidly than other fuel oils making it a non-persistent fuel [12, p. 36]. However, a report by World Wildlife Fund Canada claims that diesel spills produce more acute toxicity effects on the environment [12, p. 37]. There is a grave need to improve spill clean-up procedures and response times which currently lag behind Canada’s established procedures [11, p. 5]. A timely spill remediation response is more difficult in northern climates due to the sea ice and limited hours of daylight during part of the year [11, p. 3].

Diesel produces greenhouse gas (GHG) emissions. The National Inventory Report prepared by Environment and Climate Change Canada listed that for 2016 the equivalent of 586 kilotons (kt) [13, p. 39] of carbon dioxide were released into the atmosphere as a result of Nunavut burning diesel and other fossil fuels. The fuel used for electricity and space heating accounted for 140 kt of carbon dioxide equivalent (CO2 eq.) [13, p. 39] or 24% of the total emissions.

The World Health Organization (WHO) [9, p. para. 25] and the International Agency for Research on Cancer [14, p. para. 5] classify diesel exhaust as a known carcinogen because of the release of chemicals such as formaldehyde, mercury, and sulphur dioxide into the atmosphere [9, p. para. 24]. Although primarily linked with lung cancer, a Health Canada [14, p. para. 5] report suggests a causal relationship may exist between diesel exhaust and bladder cancer as well. Poor air quality due to diesel exhaust can negatively impact the human respiratory system, especially effecting people who suffer from asthma [14, p. para. 8]. Acute exposure to diesel exhaust is also linked to cardiovascular, reproductive, immunological, and neurological health effects [14, p. para. 6]. In addition to these health effects, the diesel generators used in each community produce constant noise pollution [9, p. para. 1].

Based on a 2015 Government of Canada Senate report, 17 of the 26 diesel generators in Nunavut [15, p. 38] were still in use despite having exceeded their operational design life. End-of-life generators are less efficient than the new variable speed generators (VSGs) on the market [5, p. para. 7]. Older generator equipment is also more prone to causing power outages [15, p. 38]. The QEC spends an average of approximately $58.4 million CAD yearly [8, pp. 4-19] (based on actual and forecasted values) to maintain and operate the existing generators. It is difficult to implement newer generator technologies or renewable energy technologies when such a large amount of funding must be put towards maintaining existing generators [9, p. para. 10]. In some communities, such as Arctic Bay, the peak electricity demand exceeds what the current diesel generator power plant is capable of supplying [16].

There are safety concerns associated with older generators. An outdated generator at the Pangnirtung, Nunavut power plant caught fire in April 2015 [17]. The fire resulted in the community relying on intermittent electricity for four days [18] in -17° Celsius weather [17] until additional small-scale backup generators could be flown in. A month-long state-of-emergency was placed on the community [18], until temporary generators were installed. However, it wasn’t until 2017 [18] that operation began at Pangnirtung’s new permanent power plant facility equipped with three diesel generators.

# Energy Costs in the North

Domestic energy rates in Nunavut are different between communities, and as of April 2019 [19] the rates were between $0.59 (Iqaluit) and $1.16 (Kugaaruk) per kilowatt hour ($/kWh CAD). In a report by Hydro Québec in 2018 [20, p. 6], per kWh rates for major cities in several other provinces were as follows: Ontario $0.13, Québec $0.07, Alberta $0.15, Manitoba $0.09. These rates were based on a monthly usage of 1000kWh to account for fixed base rates [20, p. 6]. Figure 2 shows the average residential electricity rates based on major cities across Canada for 2018 (2019 rates are used for Yukon, Northwest Territories, and Nunavut).

Figure 2 Residential Electricity Rates Across Canada

(Province rates shown are for 2018, territory rates shown are for 2019)

Sources: [20, p. 6] [21, p. 1] [22, p. 1]

Electricity rates in northern isolated communities is much higher than southern communities which are connected to the electricity grid. Electricity rates in Nunavut are the most expensive in Canada [1, p. 2]. Electricity rates are influenced by the following factors: 1) community population [6], 2) transportation costs [7, p. 1], 3) generator efficiency [8, pp. 2-3] and age of equipment [7, p. 1] (capital costs for new generators are integrated into the QEC electricity rates for each community) and 4) purchase cost of diesel [1, p. 2]. Iqaluit has the lowest cost for electricity in part because it has the largest population (over which to share the costs) of all the Nunavut communities [7, p. 1].

In order to compensate for the high cost of electricity, the Government of Nunavut subsidizes the electricity rates for residents through several organizations and departments such as the Qulliq Energy Corporation, Nunavut Housing Corporation (NHC), the Department of Finance, and the Department of Family Services [7, p. 2]. During the warmer months of April through September, a QEC subsidy is provided on the first 700kWh of electricity used per month [19]. For the remaining six months of the year (October through March) the subsidy is provided on the first 1000kWh per month [19]. Once the government subsidies are applied, the approximate electricity rate paid by Nunavummiut is $0.30/kWh CAD [7, p. 9], [23, p. 5].

As a result of these government run subsidies, approximately 80% of the territory’s energy costs are paid for by the Government of Nunavut [15, p. 36]. A 2017 International Institute for Sustainable Development report commissioned by World Wildlife Fund (WWF) Canada estimated the territorial government spends at minimum $60.5 million CAD annually subsidizing fuel in Nunavut [7, p. iii], of which an estimated annual average of $36.5 million CAD was spent specifically on electricity subsidies between the years of 2012 and 2016 [7, pp. 4, Table 2].

# Alternate Sources of Energy

Currently, the primary source of power in Nunavut is diesel. The advantages of diesel are that it is transportable, can act as a baseload, and can adjust output to match peak energy needs. The disadvantages are cost, transportation logistics, requirement for large storage tanks, and environmental hazards.

All alternatives should be considered to find a solution that works best for the location and available resources. Alternatives are discussed below.

# Solar

Solar energy has some potential, however in the North the sun does not rise for the winter months when the most energy is needed. Solar energy could be used to supplement the electricity grid during summer months and to decrease the total annual fuel volume required by a community.

Although there is not enough solar potential to provide a year-round baseload for electricity generation, Nunavut has been experimenting with the implementation of solar projects to diversify its electricity grid. The first solar project occurred in 1995 at Arctic College, Iqaluit [24, p. 59]. The College installed 3.2kW [24, p. 59] of solar panels to the building. Then in 2016, the QEC initiated a solar pilot project by installing 2kW [8, pp. 2-3] of solar photovoltaic cells on its Iqaluit power plant. The same year, a 10kW solar photovoltaic system was installed on the wall of the Arctic Games Winter arena in Iqaluit [25]. The QEC has also created a Net Metering program designed to encourage residents to generate their own renewable energy [8, pp. 2-3] which can be fed back into the grid, providing cost savings to the homeowners.

# Wind

Wind can also be used to supplement the grid, but due to inconsistent wind the power is intermittent and cannot be used to provide baseload electricity.

Nunavut has some experience with the use of wind turbines to produce electricity. However, early attempts of implementing this technology in Nunavut’s cold, northern climate proved unsuccessful. In 1987, Cambridge Bay installed four wind turbines which broke down by the early 1990s [9, pp. paras. 68-70]. A subsequent attempt to harness wind energy in Cambridge Bay resulted in the installed turbine being destroyed in a storm [9, p. para. 70]. K. Karanasios and P. Parker [24, p. 59] reported that three wind turbine projects installed and operating in the communities of Cambridge Bay, Rankin Inlet, and Kugluktuk between 1994 and 2000 were shut down because of faulty equipment.

# Biomass

Biomass is burning of organic matter for electricity. Because isolated northern communities are above the treeline, organic matter is scarce and biomass as a fuel source has little potential in the far north. It may have the potential to produce baseload power in isolated communities such as those in northern Ontario. This technology requires locations further south than Nunavut where trees are plentiful.

# Hydro

Hydro has the capability to provide the required power, but is extremely location dependent. The Northwest Territories produced 75.5% of energy used by communities from hydro power in 2013 [26, pp. 1, Figure 1].

Research was conducted into the potential for a large-scale hydro project for Iqaluit. The project began in 2005 with just over $10 million CAD [27, p. 5] invested in it over then following decade. However, the need for an additional $6 million CAD [15, p. 40] to be invested in feasibility studies caused work on the Iqaluit Hydro Project to stop in 2014 [27, p. 4]. The two-phase hydro project would require constructing dams for two locations around Iqaluit: Qikiqgijaarvik (Jaynes Inlet) and Tungatalik (Armshow South). It was estimated that between the two sites, the project could produce 16 to 23.4 MW of electricity for Iqaluit [15, p. 40]. If constructed, this hydro project could generate over two-times the required electricity necessary to meet Iqaluit’s annual needs (based on Iqaluit’s forecasted demand of 61456 MWh [8, pp. 4-24] for the 2018/2019 year).

There are drawbacks to the use of hydroelectricity: implementation of the hydro technology is geographically dependent. Additionally, damming rivers or lakes can require flooding of the local area impacting the aquatic ecosystem and surrounding natural environment [28, pp. paras. 5, 6].

# Nuclear

Nuclear power currently needs large expensive infrastructure and is only cost effective for high output situations [29]. Since the communities in Nunavut are small with low individual energy needs and too far apart to join in a single energy grid, current available nuclear technology is not feasible in Nunavut.

Nuclear technology may be suitable as a future option when Small Modular Reactors (SMR) become available [29]. Theoretically, these could be as small as 3MW output and could be designed to have a footprint as small as a single shipping container [29]. This technology could take decades to develop before it is commercially available. When it is ready, there could be significant resistance to its adoption due to perceived safety concerns.

# Geothermal

Geothermal energy is created from the heat deep in the earth’s crust. This energy is most readily available in places with volcanic activity where high temperatures can be found near to the surface. In northern Canada, there is no near surface volcanic activity, so it will require drilling to extreme depths to produce suitable heat for power generation. The thermal gradients in the North are not well defined due to a lack of local data. The global average is approximately 25°C/km [30], which would mean that at a depth of 4km the temperature would be 100°C. Due to the lack of available data and approximately 500m of permafrost as surface cover [31], EAL is making an assumption that the thermal gradient is less favourable at approximately 15°C/km which would result in a temperature of 100°C at a depth of about 7km. Further work should be carried out to determine actual thermal gradients before any systems are designed.

The QEC has expressed an interest in exploring the possible use of geothermal technology. In 2018, a feasibility study exploring the possibility of using geothermal energy in Nunavut was produced for the QEC [32, p. i]. This study is the necessary initial step in evaluating the geothermal characteristics of Nunavut’s communities based on the local geology. If studies continue, the second step after determining areas with favourable geothermal conditions will be to drill thermal gradient boreholes [32, p. iii]. The thermal gradients will be used to more accurately assess the necessary depth required to reach suitable temperatures and the estimated electric or thermal power that can be generated.

# Geothermal Technology

# Advantages/Disadvantages

The advantages of geothermal energy include it being a clean energy source, available everywhere on the planet so long as the wells are drilled deep enough, it does not rely on weather, operates 24/7 [33], can be scaled to any size of power plant based on local needs, and does not require an external fuel source [33]. Geothermal energy is not dependent on external political and economic factors which cause fluctuations in oil and gas prices [34, p. 4]. In addition, geothermal energy can use the “waste” residual heat after electricity production for district heating usage [33], which could greatly reduce the amount of electricity required for heating. This is especially important in northern areas where most energy is spent on heating. Unlike other renewable energy sources such as wind and solar, geothermal power plants do not require large amounts of land for construction or operation [34, p. 5]. A reduced industrial land footprint results in less destruction of the natural environment, and therefore, less disruption to animal habitats and migratory pathways [33].

The main disadvantage of geothermal energy is that it can be quite expensive to drill to the depths required for the system to work. However, geothermal technology is likely still cheaper than shipping in diesel indefinitely. Besides from the high cost of implementing the technology, most of the negative impacts of the energy source are associated with the construction of the project: noise issues (although new drill rig technology is designed to minimize noise disturbances [34, p. 9]), difficulty in transporting the drill rig equipment, electricity consumption of the drill rig [35], and potential pollution or diesel fuel spills caused as a result of drilling [36, p. 2]. Increased geothermal plant maintenance costs can occur as a result of mineral deposits and corrosion on the well pipes [37, p. 364].

Geothermal technology has not been widely explored in Canada. Unfamiliarity with the technology can present challenges for geothermal companies attempting to secure private investors [38]. Additionally, a positive mindset about the technology is necessary in communities affected by the construction of the wells and power plant [39]. This requires educating, communicating, and collaborating with community members who may previously be unaware of the technology.

# Enhanced Geothermal Systems (EGS)

Based on the local geology of the North, bedrock at depth is likely to be granite and gneiss [40] and it is unlikely for there to be an aquifer at the depth where significant temperatures are reached. In this geology, an Enhanced Geothermal System (EGS) would be used.

An EGS system consists of two wells: An injection well and an extraction well. Hydraulic fracturing under very high pressures is used to create fractures in the rock between the two wells through which a fluid is circulated. The fluid is pumped through a surface power plant where the thermal energy is converted to heat [41].

The theory behind such a system is not new; EAL’s research has found references to this system as early as the 1970s [41]. These sources discussed several methods for optimizing hydraulic fracturing for heat extraction and several methods for converting the heat into electricity. During the early stages of EGS technology, methods for using low grade heat (the geothermal condition expected to be found in the arctic region) were still theoretical and not ready for commercial use.

# Organic Rankine Cycle (ORC)

EAL is assuming that temperatures will reach approximately 100°C at a depth of 7km (see Section 5.6). This temperature would be considered a low-grade heat; in order to run optimally, most systems use a much higher temperature. However, with commercially available technology which makes use of the Organic Rankine Cycle (ORC), low temperatures can be used to generate electricity.

There are several manufacturers currently selling equipment that would be suitable for this purpose. One example of an existing commercial system is made by Climeon. The Climeon system [42] is a modular system consisting of 150kW generators that can be connected in series or parallel depending on the heat and water flow rates available. It can operate with temperatures as low as 70°C using the Organic Rankine Cycle.

The Organic Ranking Cycle works by transferring heat from the source through a heat exchanger to a working fluid within the generator. This fluid can be of varying types, but the main parameter is that it has a lower boiling point than water. This fluid boils, creating steam which is then fed through a turbine, cooled, and then recycled in a closed loop system. If implemented in the North, the extreme cold temperatures would aid in cooling which may increase the efficiency of the ORC system.

# Combining Solar Thermal with Geothermal

A relatively low-cost method for improving the overall performance of a geo-electrical system is to add a solar thermal collector into the system. Such a solar collector uses mirrors to concentrate light onto a tube containing fluid (Figure 3 below).



Figure 3 Example of parabolic trough type solar collector

Source: [43]

A number of methods for integrating solar thermal heat into a geothermal system are proposed by Li, et al. [44]. Based on the low temperature heat source that would be expected in the North, it is likely that the best method would be to use solar energy to boost the temperature of the fluid being extracted from the geothermal well. An example of a combined hybrid system is shown below in Figure 4. In this example, the fluid is extracted from the well, and then it is routed through a heat exchanger that is heated by the solar collector. This higher temperature fluid is then pumped through the ORC generator to create electricity. The ORC generator operates more efficiently at higher temperatures. If there is enough energy added to the system from the solar collector, the returning fluid may be higher than the extracted fluid.

Injection

Well

Extraction

Well

ORC Generator

Fracture Zone

Solar Collector

Heat Exchanger

Higher Temp

 3-7km

Figure Hybrid Geothermal-Solar System

Source: Author’s Own

# Case Studies

The first use of geothermal technology to produce electricity occurred in 1904 at Larderello, Italy [37, p. 363]. Initially, the Laderello plant was only capable of generating “enough [electricity] to power five light bulbs” [45, p. para. 3]. The Larderello plant has been in permanent use as of 1913, and is capable of producing up to 360 MWe [37, p. 363]. Beginning in the 1970s [45, p. para. 3], advances in geothermal technology have resulted in EGS capable of being used to access the Earth’s heat without the presence of an underground water source. Globally, this technology is in the early stages of implementation to reach heat deep within the Earth that was inaccessible using traditional geothermal systems.

Canada has just begun to enter into the geothermal energy sector. Up to this point, Canada has used geothermal resources sparingly and only for the production of heat, not electricity [36, p. 1].

# Fort Liard, Northwest Territories, Canada (Incomplete Project)

A geothermal demonstration project being researched in 2011 by geothermal energy company Borealis GeoPower in partnership with Acho Dene Koe First Nation was intended to produce electricity for the community in Fort Liard, Northwest Territories [39]. Fort Liard had significant resource assessments because of previous fossil fuel exploration in the area. The intention was to access a 180° Celsius hot water reservoir by drilling wells to a depth of 4km beneath the ground surface [39, p. para. 12]. The geothermal plant would need to produce around 600 kilowatts (kW) of electricity to meet the energy demands of the community [39, p. para. 15]. However, by 2014 [46] the estimated $15 million CAD development [39, p. para. 7] was stopped and federal funding was lost when Borealis GeoPower and Northwest Territories Power Corporation could not reach a power purchase agreement [46].

# DEEP, Saskatchewan, Canada (Under Construction)

The first Canadian geothermal energy production project to reach the construction stage is in Saskatchewan. The private energy company DEEP (standing for Deep Earth Energy Production) is planning to use geothermal energy to generate electricity [33]. The project is located close to the city of Estevan in southeastern Saskatchewan [33, p. 'Project Scope']. This location was selected because of the favourable geothermal conditions discovered during the initial feasibility stages. The company found a hot sedimentary aquifer in the Williston Basin approximately 3500m [33, p. 'Project Scope'] below the ground surface which will produce water temperatures of approximately 120° Celsius [47, p. para. 9].

In 2014, with funding assistance from the federal and provincial governments, DEEP invested $2 million CAD into a prefeasibility study [33]. DEEP has raised $51.3 million CAD for the construction and analysis phase of the project [48]. The federal government of Canada has invested $25.6 million CAD into the project through Natural Resources Canada’s Emerging Renewable Power Program [49]. Natural Resources Canada previously contributed $1.35 million CAD towards prefeasibility and test drilling [49]. The provincial government of Saskatchewan provided $1 million CAD towards the prefeasibility study and an additional $175 000 CAD for the construction phase [48]. Private investments into the project also had be to secured, which proved challenging because geothermal energy is new to Canada [38].

Drilling of the first well hole was completed in December 2018 to a depth of 3530m [33]. This is the deepest well in Saskatchewan [48]. Drilling of the second hole did not begin until October 2019 [49]. The time in between drilling the holes was used to run flow and simulation tests and analyze the components of the brine [33]. The testing is used to determine the direction and depth of the second well hole. The well holes were designed to begin at the same ground location, but veer apart from one another underground. The injection well (first hole) was drilled vertically, while the production well (second hole) is being drilled directionally [49]. This will result in the wells being approximately 1.5km apart horizontally at their deepest elevations [33].

DEEP aims to have the plant operational by 2022 [33]. The company needs to allot 12-16 months for the ORC plant to be ordered and installed [49]. The increased interest and development of the ORC is the reason that DEEP can use geothermal technology to generate electricity from a low-enthalpy heat source. The U.S. Office of Energy Efficiency & Renewable Energy defines low-temperature geothermal energy as underground resources containing temperatures below 150° Celsius [50, p. para. 3]. These temperatures are not high enough to convert water to steam and therefore are not suitable for use in traditional steam systems. The ORC relies on the use of a heat exchanger to transfer the heat energy from a low-enthalpy water source to another liquid with a lower boiling point. Steam is then generated from the second liquid, which in turn runs a turbine and generates electricity [47, pp. paras. 7-8].

The plant is designed to initially generate 5MWe [48]. DEEP has designed the plant generator capacity to be scalable, so that over the long term, electricity generation can be increased substantially [33]. In addition to electricity generation, DEEP is interested in selling the waste heat to the local industries, such as farming, which can utilize the heat in greenhouse operations [38]. DEEP is also exploring the possibility of a mining component to the geothermal project, as they have obtained the mineral rights to the area around the wells [38]. The brine (a combination of water and minerals) retrieved from the earth is high in elements which could potentially be extracted by the company [38].

Saskatchewan’s DEEP geothermal energy project is the most advanced geothermal project underway in Canada. However, it bears little resemblance to the conditions expected to occur in Canada’s north. Low-enthalpy systems, deep drilling, and dry rock characterize the subterranean conditions anticipated to occur in Nunavut. Globally, companies are just beginning to explore these less favourable geothermal conditions as potential energy sources. There are two notable projects nearing completion in Europe: United Downs in Cornwall, and Otaniemi in Finland. Additionally, low-enthalpy, modular, geothermal units in Alaska offer an inexpensive alternative.

# United Downs, Cornwall, UK (Under Construction)

The United Downs Industrial Estate in Cornwall, United Kingdom (UK) is the site of a new geothermal energy demonstration plant. The location was chosen because of the ‘Cornubian Batholith’ granite bedrock in the area [35]. Cornwall has higher geothermal gradients than elsewhere in the United Kingdom because of the occurrence of radiogenic materials in the granite. The elements potassium, thorium, and uranium produce heat as a result of the radioactive decay process [51, p. 'Hot rocks']. This results in higher temperatures being accessible at a shallower depth beneath the ground surface. The geothermal temperatures 5km below Cornwall’s ground surface were measured to be approximately 190° Celsius [52]. The geothermal plant is being designed to produce a minimum of 1MWe [53]. A maximum of 3MWe can be generated from the power plant and fed into the existing grid [53].

The company Geothermal Engineering Limited (GEL) is responsible for the project [54]. The location of the project at the United Downs Industrial Estate showcases several of the advantages of geothermal energy technology. Firstly, the drill site and power plant does not occupy a large amount of land [35], thereby allowing the power plant to be situated close to the community being served. Secondly, the power plant does not require high quality land. This means that lands classified as brownfields can be repurposed efficiently for use as geothermal plant locations. This is the case with the United Downs project, which is situated in an industrial brownfield [35]. Advanced drill rig technology, such as the Innova Rig produced by German company Anger’s Söhne [34, p. 9], have been specifically designed to satisfy allowable noise limits for drilling in urban environments [35]. Construction on Geothermal Engineering Limited’s United Downs project began in November 2018 [55] with the drilling of the injection well to 2393m in depth [56]. The size of the well holes taper from a maximum of 61cm in diameter for the production well at ground surface to 22cm in diameter at the deepest location [55]. Although the wells were being drilled into hot, dry, granite bedrock, engineers designed the bottom of the wells to intersect the Porthtowan Fault Zone [56]. By targeting this fault zone, the well basement is in an area of naturally increased permeability.

Drilling of the production well to a depth of 5275m [56] was completed by July 2019 [55]. The semi-automated hydraulic drill rig was in use 24-hours a day. Despite continuous operation, almost eight months was spent to complete drilling of the two holes because of the depth and type of rock encountered [55]. During the drilling and stimulation phase, the area was monitored for micro-seismic events created from the pressurized water pumped into the well [57]. In addition to monitoring for micro-earthquakes, seismic monitoring devices were used to record and map the flow of water in the geothermal reservoir from the injection well through the fault zone [57].

The production testing is scheduled to finish by Spring 2020 [55]. GEL has raised £18 million for the project through the European Regional Development Fund, Cornwall Council, and private investors [54].

# Eden Project, Cornwall, UK (Pre-Construction)

A large portion of the time and financial resources in a deep EGS project is due to the drilling process. To optimize use of necessary drilling and analysis time, some companies are looking into the use of co-axial systems as an intermediary step before drilling the second hole in a closed-loop geothermal system [58]. The co-axial system relies on one well hole to inject water and extract heat from within the earth. The system works by having cold water travel down an outer tube, and the heated water pumped up the insulated interior tubing [58]. The co-axial system is not as efficient as the two-well closed-loop system, and is therefore generally only used to produce heat, not electricity. However, heat can be generated, sold, and distributed to the community, through use of a co-axial system while the analysis and optimization of the second (production) well is taking place.

The Eden Project, a research geothermal plant, has conceptual plans to make use of a 4.5km deep co-axial system for Phase I of their project, while Phase II will involve drilling a second well hole to form a closed-loop electricity generating system [58]. The Cornwall-based Eden Project is still in the early stages, having only begun preparation and procurement activities in 2019 with an aim to begin drilling by Summer 2020 [58].

# Otaniemi, Espoo, Finland (Under Construction)

Similar technology to that used at the United Downs project in Cornwall is being utilized in Finland for an even deeper geothermal well project. The Finnish energy company, St1 Nordic Oy [59, p. 1], is positioning itself to be a leader in the renewable energy sector by financing a geothermal pilot project in the district of Otaniemi, Espoo, Finland [60].

Otaniemi is a highly populated urban district in Finland which includes Aalto University and Meilahti hospital [61, p. para. 8]. The selection of Otaniemi for this pilot project once again highlights the advantages of geothermal technology: limited land requirements and no hazardous emissions during operation. St1 partnered with professors and researchers from the Institute of Seismology at the University of Helsinki to study the seismic events recorded during the drilling and stimulation phases of the project [62, p. para. 3]. Although micro-seismic events were observed as a result of the project, the magnitude from the recorded events were below the recommended limits set by the Institute of Seismology upon request of Finland’s Ministry for the Environment [61, pp. paras. 4, 14].

Otaniemi is located in the Fennoscandian Shield [59, p. 2] which contains low-enthalpy geothermal resources, even at depths of 8km below the ground surface. The geothermal gradient in the Fennoscandian Shield is on average 8-15°C/km [59, p. 2]. In order to reach high enough temperatures St1 drilled through the granite to a depth of 6.4km [59, p. 1] - the world’s deepest geothermal well to date [63, p. 'Question and answers' ]. At this depth, it is estimated that the water will reach temperatures between 100 and 120° Celsius [59, p. 3]. The well hole sizes varied from over 100cm diameter at the surface to 20cm diameter at basement [60, p. para. 4].

However, drilling 6.4km into Precambrian granite formations [59, pp. 1-2] proved to be challenging for the company. The project began in Summer 2015 [60, p. para. 2] with the drilling of a roughly 2km deep borehole [59, p. 1] to sample the material composition and assess seismicity. Drilling of the first well began in April 2016 [64], using a combination of water hammer and air hammer drill rig technologies [64]. Initial statements from St1 indicated that drilling would be completed by 2017 [60, p. para. 5], but the first phase of drilling was not finished until Spring 2018 [61, p. para. 10].

The second phase of drilling (completion of the production well to depth) is expected to finish by April 2020 [65] after 30 days of stimulation [66] and between five to seven months of analysis [62, p. para. 1]. The company had to halt production for approximately six months [64] in 2017 in order to investigate alternative drilling technologies, as the water hammer technology had become uneconomical [64]. Not only is drilling deep into the ground expensive and time-consuming, but it is also an energy intensive process. The large drill rig used at the St1 Otaniemi site requires access to up to 6.3MW of electricity for operation [60, p. para. 3].

St1 is aiming to have the geothermal plant operational by October 2020 [65]. The geothermal plant is designed to produce to up 40MW of thermal power (MWt) which will be sold for district heating [63, p. 'A simple process...'].

# Chena Hot Springs, Alaska, USA (Completed)

In contrast to the deep geothermal resources being explored in Europe, an American project started in 2004 [67, p. 2] successfully harnessed the energy from low heat, shallow hot springs. The Chena Geothermal Power Plant is located at Chena Hot Springs Resort in Alaska. The Chena Resort, which commissioned the project, was able to retrieve water with a temperature of approximately 73° Celsius from the hot spring [67, p. 3]. The injection well was drilled to a depth of 214m and the production well to a depth of 217m [67, p. 5].

The generator equipment was supplied by United Technologies Corporation (UTC). UTC received a grant through the United States Department of Energy to develop their modular generator system designed to use low-enthalpy waste heat from industrial processes to produce electricity [67, pp. 1-2]. The generators operate using the ORC (also referred to as a binary system). As a result of designing the generators for low-heat applications, UTC did not have to rely on custom components for the equipment. Instead, UTC was able to incorporate mass-produced components such as chillers commonly used in air conditioning units [67, p. 2]. This decreased the cost of the generator unit and increased accessibility to parts [67, p. 2], making the technology more feasible for replication and installation elsewhere.

Two generator units (ORC1 and ORC2) were installed at the Chena Hot Springs Resort during August and December of 2006 [67, p. 3]. The modular design of the generators allowed most of the equipment to be installed by the Chena Power staff. Only the final connection procedures required the UTC experts [67, pp. 5-6]. Ease of installation and maintenance are major advantages when using energy technologies in remote locations.

The generators were designed to produce 200kWe [67, p. 1]. After installation, it was discovered that ORC2 was more efficient than the first generator unit due to the added feature of an air-cooling system (in addition to a water-cooling system) [67, pp. 4, 6]. Based on these results, ORC1 is intended to be modified to include the air-cooling system which produces a higher efficiency due to a larger differential between the hot water source and the cold air during the winter months. The inclusion of the air-cooling system to ORC2 resulted in the generator producing 220kWe [67, p. 4] throughout the winter. The project cost the Chena Hot Springs Resort approximately $2.0 million US [67, p. 6] with some government funding being provided.

# Cost

The only geo-electric project underway in Canada is Saskatchewan’s DEEP geothermal energy project. The DEEP project is expected to cost over $50 million CAD [48]. However, this cost corresponds to a location in southern Saskatchewan and drilling less than 4km into the earth [33] – conditions very different to those expected in Nunavut. Costs of drilling in Nunavut are anticipated to be significantly higher due to difficulty in transporting equipment. In general, the cost of drilling geothermal wells increases exponentially with depth [68, p. 12], even without the added challenges of Nunavut’s cold climate and permafrost layer.

An important consideration is the cost associated with operating the electric drill rig. Based on the Anger’s Söhne Innova Rig technology, which requires an energy input of up to 6.3MW [60, p. para. 3] a drill rig operating continuously, 24-hours a day, for a year, would consume 55188 MWh of electricity at peak usage rates (although the drill may not always be operating at peak consumption rates). Using the 2015/2016 generator efficiency rate in Iqaluit [8, pp. 4-21] as an example, 55188 MWh of electricity would require 13.9 million litres of diesel at a cost of $16.0 million CAD to the community. This is the equivalent amount of diesel necessary to provide electricity to Iqaluit for almost a year (93% of the community’s 2015/2016 electricity generation).

Electricity demands in Nunavut’s communities could be reduced if the waste heat from the geothermal plant is used for district heating purposes. A 2015 report prepared by the Standing Senate Committee on Energy, the Environment and Natural Resources states that 15% of the Nunavut Housing Corporation costs are spent on space heating [15, p. 41]. Therefore, utilizing waste heat could reduce heating costs for the government.

While installation of a geothermal electrical system may be expensive, so too are the costs associated with the use of diesel in Nunavut.

A financial report released by QEC recorded fuel consumption at 50.0 million litres [8, pp. 4-21] and an associated fuel and lube cost of $55.3 million [8, pp. 4-21] for the 2015-2016 year. The fuel consumption amounts are forecasted to increase with population growth and increased energy demands. QEC reported that 2015-2016 operation and maintenance (O&M) of the diesel power plants cost $56.3 million [8, pp. 4-19].

The current use of diesel in Nunavut is expensive, and likely to become even more expensive in the future. The Pan-Canadian Framework for Clean Growth and Climate Change predicts that if the carbon tax is implemented, a price of $50 CAD will be associated with each tonne of GHG emitted [7, p. iii]. That means Nunavut’s 586 kt (produced in 2016) [13, p. 39] of CO2 eq would cost the territory an additional $29.3 million CAD each year. While the carbon tax would increase the monetary penalty of polluting, there remains unquantified and indirect costs associated with the health and environmental effects of oil spills and burning diesel fuel [23].

The Pembina Institute reports that the federal government is committed to helping Indigenous communities transition away from diesel through their Pan-Canadian Framework on Clean Growth and Climate Change [69, p. 42]. Numerous funding organizations have been established to assist in these efforts including, amongst others: Clean Energy for Rural and Remote Communities, Indigenous Off-Diesel Initiative, and the Arctic Energy Fund. These three programs alone can provide $640 million CAD in funding for energy security and renewable energy projects over the next ten years [69, p. 42]. This money is necessary in order to invest in large, renewable energy projects. Currently, the QEC is spending millions [8, pp. 4-19] maintaining and improving Nunavut’s existing energy infrastructure [15, p. 38]. Without additional funding sources, it is difficult for the QEC to allocate financial resources towards capital intensive renewable energy projects.

A November 2019 news article placed the cost of a new diesel generator power plant at $32.4 million CAD for the community of Arctic Bay [16]. However, this is much less than the capital required for proposed renewable energy projects. A QEC report listed the construction cost of the Iqaluit Hydro Project at $356 million CAD [27, p. 4]; in a March 2017 news article, it was reported that the QEC estimated the cost could reach $500 million CAD [70]. The hydro project was abandoned in 2014 [27, p. 4] due to increased feasibility study costs [15, p. 40]. The estimated lifespan of the Iqaluit Hydro Project was 100 years [27, p. 3]. Another possible project, a hydro-electric grid connecting Churchill, Manitoba with the southern five communities in Nunavut’s Kivalliq region, is estimated to cost $904 million CAD [71]. A 2015 article suggests this project could be financially feasible despite the large capital required, as it would save approximately $40 million CAD each year by reducing dependency on diesel [71]. The project is anticipated to have an operating lifespan of 40 years [71], consistent with the lifespan of other technologies such as the proposed power plant for Arctic Bay [16].

# Conclusion

The use of low-enthalpy geothermal reservoirs as an energy source is an emerging technology being researched in Canada and globally. There are several international projects underway or set to complete in 2020. Lessons from these projects will be invaluable as the potential for geothermal energy is explored in Canada’s north. Geothermal energy presents itself as a viable solution for an energy source which can be located within the community it is designed to serve. Advanced drill rig technology combined with noise reduction techniques have allowed drilling projects to operate in urban environments.

However, drilling several kilometres deep into the bedrock is a new frontier for energy companies. Time, money, and electricity resources must be invested into the drilling procedure. Finland’s Otaniemi geothermal heat plant includes the world’s deepest well at 6.4km [59, p. 1], [63, p. 'Questions and answers']. The estimated heat gradient in Nunavut suggests that 7km would be required to reach bedrock of sufficient heat. This would require wells to be almost 1km deeper than currently exist in the world.

Transportation of the drill rig to remote locations is an additional challenge facing Canada’s northern communities. Companies assessing geothermal energy potential in Nunavut will also need to consider the cost of supplying electricity to run the drill rig for an extended period of time. Access to fuel is limited in the north and the need to ship in additional fuel will be a further time and economic constraint.

As evident from the current geothermal projects being undertaken, the time commitment to construct a deep-well geothermal project is significant. Prefeasibility studies, financing, equipment procurement, technology development, and technical expertise must all be secured. The decision to build a geothermal power plant is likely to lead to a five to ten-year commitment. Projects involving geothermal plants which utilize low-enthalpy heat sources for electricity generation are limited. Instead companies have focused on providing district heating from low-enthalpy geothermal resources.

Despite the large capital costs associated with geothermal projects, the development of geothermal resources in Nunavut may be viable as a result of the high prices on diesel imports and the potential implementation of the carbon tax. Nunavut currently remains energy-dependent on diesel and other imported fossil fuels while disproportionately suffering the effects of climate change. It is necessary to consider solutions that will allow Nunavut to have increased energy security. However, all energy projects being explored must involve consultation and communication with the Indigenous communities of Nunavut. Inuit hold the land and water rights in Nunavut [72], and it is ultimately their decision as to how these natural resources should be used or altered.

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