Alternative heating systems for northern remote communities: Techno-economic analysis of ground-coupled heat pumps in Kuujjuaq, Nunavik, Canada

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HIGHLIGHTS

- Ground source heat pump as a clean and efficient heating alternative
- Applications in remote, subarctic conditions
- Shallow geothermal potential mapped to evaluate project viability
- Economic attractiveness reviewed with 50-years life-cycle cost analysis
- Compression heat pump and solar panels hybrid as cheap and CO_2-reducing solution

ABSTRACT

Nunavik is a subarctic remote region covering the northern third of Québec, Canada, where low efficiency and environmentally adverse diesel furnaces are currently used to meet residential heating demand. Studies focusing on building heating alternatives in subarctic climate are limited and hence, this work can help with the development of such systems in remote off-grid communities. Shallow geothermal potential was mapped for Kuujjuaq, the largest village in Nunavik. Four ground-coupled heat pump scenarios were analysed for a simulated 5-occupant residential dwelling, with heating needs of 71 MWh/year. Resulting maps show a relatively high ground potential for such cold region, ranging between 5.8 MWh/year and 22.9 MWh/year per borehole for heat exchanger lengths of 100 m to 300 m. A 50-year life-cycle cost analysis of such systems reveal that a compression heat pump with electricity derived from solar photovoltaic panels has a net present cost as low as approximately CAD$179,000, representing the most economically attractive heating option in Kuujjuaq as compared to the currently subsidized, diesel furnace heating at CAD$277,000. This work verifies that shallow geothermal energy through state-of-the-art heat pumps is a financially interesting option in Kuujjuaq. Results can be extended to similar subarctic settings in Canada and worldwide.

Keywords: renewable energy, geothermal, Nunavik, ground-coupled heat pump, G.POT, life cycle cost

1. INTRODUCTION

Nunavik, home to 14 Inuit villages with a total of 12,300 inhabitants, is a remote region covering the northern third of Québec province, Canada. These communities are not connected to Québec's electrical grid and hence, are reliant on diesel power plants and furnaces to meet their electricity and building heating demands. In 2018, the price of fuel oil was $2.03/l, which is subsidized by the local government to $1.63/l [1]. Such high cost of fuel is partly associated with the additional cost of fuel transportation from the south to Nunavik. Additionally, diesel is only shipped once a year to these communities. As a result, they are forced to purchase annual supplies of diesel fuel on the spot market, making diesel price volatile in this region [2]. Kuujjuaq, the regional capital of Nunavik, experiences a low annual average temperature of -5.4°C and an annual average of 8,520 heating degree days below 18°C (HDD_{18}). In Nunavik, houses are typically built to meet the strict regulatory standards for adequate insulation of building envelopes [3]. Despite this, the harsh climate result in high building heating requirement. Furthermore, between 2006 and 2011, the Inuit population in Nunavik increased by 12% [4]. This combination of high fuel cost, high building heating requirements, increasing demand and adverse environmental impact of fossil fuel combustion calls for the development of new approaches, specifically via renewable energy sources to supply clean, locally-generated and reliable energy in these off-grid communities.

Several alternative energy options have been studied to date. In 2011, hybrid wind-diesel turbine was Hydro-Québec's preferred alternative to reduce fossil fuel consumption in power generation [5]. However, this option was rejected by the communities of Inukjuaq and Whapmagoostui-

Kuujjuarapik, that preferred hydro-power and connection to the integrated power grid, respectively. Karanasios and Parker [6] reviewed past renewable electricity projects and the available resources for electricity generation in Nunavik. They concluded that despite the available wind resources, wind generation is presently not financially viable in these communities. Yan et al. [7] evaluated alternative technologies such as wood pellets combustion, waste gasification and natural gas through a multi-criteria decision analysis, and ranked the first as the best option for building heating. However, wood pellets need to be imported to the area as there is no local supply, which would mean that energy generation is only partially independent. Additionally, the utilisation of specific shallow geothermal energy technology such as heat pumps was not considered in their analysis. In Nunavik, preliminary evaluations of geothermal resources have been carried out by Comeau et al. [8], Giordano et al. [9] and Miranda et al. [10,11]. Nevertheless, the potential of geothermal energy as a possible solution has not been fully assessed to date. Thus, in this study, ground-coupled heat pump (GCHP) is proposed as a viable alternative to the low efficiency and high greenhouse gas (GHG) emitting diesel furnaces currently used for heating buildings.

GCHP has been successfully installed in cold regions around the world, although its economic viability may vary according to the energy source used to run the GCHP and the cost of that energy. Pike and Whitney [12] reviewed the economic performances of seven GCHPs with vertical borehole heat exchangers (BHEs) in Alaska. The Cold Climate Housing Research Centre [13] in Fairbanks, Alaska found that a GCHP with horizontal BHE performed better-than-expected for the first four years, with coefficient of performance (COP) ranging between 2.82 to 3.69, which plateaued in year 5. In these two studies, the authors noted that the cost effectiveness of GCHP, however, depends on the cost of oil and electricity in the area. The lower the cost of oil, the less cost effective the GCHP system would be compared to the conventional oil furnace heating system. Similarly, Healy and Ugursal [14] concluded that the GCHP with horizontal BHE in Halifax, Canada is more economically viable compared to the oil heating system used in the region.

The main challenges of operating GCHPs in such cold climate relate to the low ground temperature, lower GCHP efficiency, high building heating needs and the fact that the usage of electricity to run the GCHP is not advised by Hydro-Québec as electricity in Nunavik is generated by diesel. Thus, the technical viability of shallow geothermal technology has been tackled in several recent studies. Fontaine et al. [15] proposed a new analytical model for horizontal heat exchangers and applied it to a case study of permafrost stabilization in Kuujjuaq, with heat extraction as a by-product. Heat exchangers at a depth of 2.5 m can easily keep the ground frozen during summer and at the same time cover the heating needs of the building. Belzile et al. [16] simulated the performance of compression and absorption heat pumps coupled to horizontal ground heat exchangers to partially cover the heating needs of a building in Kangiqsualujjuaq and demonstrated that an absorption heat pump could provide the lowest operating cost with 40% savings on fuel oil consumption. Giordano and Raymond [17] evaluated the 5-years technical performance of borehole thermal energy storage system for a drinking water facility in Kuujjuaq, showing that a 50% penetration is technically feasible even in this subarctic climate. Giordano et al. [18] simulated the fluid temperature trend of vertical closed-loop heat exchangers and the ground temperature over 10 years, highlighting that 35 W/m can be sustainably retrieved from the

Kuujjuaq subsurface by a 300-m-deep BHE. A simple financial analysis defined a BHE drilling and installation cost of CAD$150/m as a threshold to guarantee interesting payback times. However, the economical feasibility of such systems through detailed life-cycle cost analysis has never been addressed.

This study aims to quantify the shallow geothermal potential of Kuujjuaq, the capital of Nunavik, by estimating the maximum amount of energy that can be sustainably extracted with a GCHP coupled to vertical BHE installed in shallow subsurface with a relatively cold temperature of slightly above 0°C, and where this system has never been used in such cold environment. The methodology applied were as follow:

1. Mapping of the shallow geothermal of Kuujjuaq using ground thermal properties data with a geographic information system- (GIS-) based workflow.
2. Simulating the heating load of a typical residential building In Kuujjuaq using the local weather data.
3. Calculating the 50-years life-cycle costs of business-as-usual heating scenario of using diesel furnace and four alternative heating scenarios using GCHP.

This work is expected to serve as a basis for future studies focusing on the applications of GCHP in subarctic conditions, where low ground temperature, unbalanced heating or cooling loads, high cost of BHE drilling and installation, and remoteness of the communities can significantly affect its techno-economic feasibility. However, through this combination of methods, the shallow geothermal resources available, as well as the economic feasibility of the implementation of the GCHP technology can be quantified and analysed for any region globally.

2. METHODS

2.1 Shallow Geothermal Potential Mapping

The G.POT method developed by Casasso and Sethi [19] (Eq. 1) estimates the shallow geothermal potential or the maximum thermal energy that can be sustainably extracted annually by a closed-loop BHE in a homogeneous subsurface. This method can be used for both cooling and heating mode. However, the geothermal potential of Kuujjuaq is calculated only for heating mode as there are very low cooling requirements in the study area.

$$\bar{Q}_{\mathrm{BHE}} = \frac{0.0701\cdot(T_0 - T_{\mathrm{lim}})\cdot\lambda\cdot L\cdot {t'}_{\mathrm{c}}}{-0.629\cdot {t'}_{\mathrm{c}}\cdot\log({u'}_{\mathrm{s}}) + (0.532{t'}_{\mathrm{c}} - 0.962)\cdot\log({u'}_{\mathrm{c}}) - 0.455{t'}_{\mathrm{c}} - 1.619 + 4\pi\lambda\cdot R_{\mathrm{b}}} \qquad (1)$$

The geothermal potential $\bar{Q}_{\mathrm{BHE}}$ (MWh/year) is dependent on the maximum possible temperature difference between the ground and the fluid $T_0 - T_{\mathrm{lim}}$ (°C), the ground thermal conductivity λ (W/mK), the borehole length L (m), the thermal resistance of the borehole R_{b}

(mK/W). The three non-dimensional parameters $u'_{\mathrm{s}}, u'_{\mathrm{c}}$ and t'_{c} depend on ground heat capacity (ρc), borehole radius, simulated lifetime of the system, length of the heating season and the load cycle. Tables 1 and 2 summarize the input parameters used to map the geothermal potential. To address the potential problem of thermal imbalance due to long-term heating-only operation of the system, a conservative value for the threshold fluid temperature T_{lim} of -5°C was assumed.

Table 1. Thermal conductivity and heat capacity for unconsolidated sediments and bedrock [9,20].

	Types	λ saturated (W/mK)	ρc saturated (MJ/m^{3}K)
Bedrock Lithology	Paragneiss	2.7	2.4
	Diorites	3.0	2.4
	Granites	2.9	2.3
	Gabbros	3.0	2.4
	Tonalites	3.4	2.3
Unconsolidated Sediments	Marine	1.5	3.0
	Alluvial	1.4	3.2
	Glacial Till	1.6	3.0
	Outcrops	0	0

Table 2. Parameters used for mapping the geothermal potential of Kuujjuaq [21].

Parameter	Symbol	Values	Unit
Threshold fluid temperature	T_{lim}	-5	°C
Borehole length	L	100/200/300	m
Undisturbed ground temperature	T_0	1.0/1.75/2.75	°C
Borehole radius	r_{b}	0.038	m
Simulated lifetime	t_s	50	years
Length of the heating season	t_{c}	270	days
Borehole thermal resistance	R_{b}	0.1	mK/W

Figure 1 shows the unconsolidated sediments and bedrock geology of Kuujjuaq [22]. Using both QGIS 2.18.21 (QGIS) and Surfer® 9 (Surfer) software [23,24], a depth layer consisting of existing data of depths of unconsolidated sediments obtained from the field study was created and interpolated with the Kriging method using a 300 x 300 m grid spacing to cover the entire study area (Fig. 2). The unconsolidated sediments are found above the bedrock layer. Where no unconsolidated sediments are found, the bedrock layer shows as an outcrop, which are colored white in Figure 2.

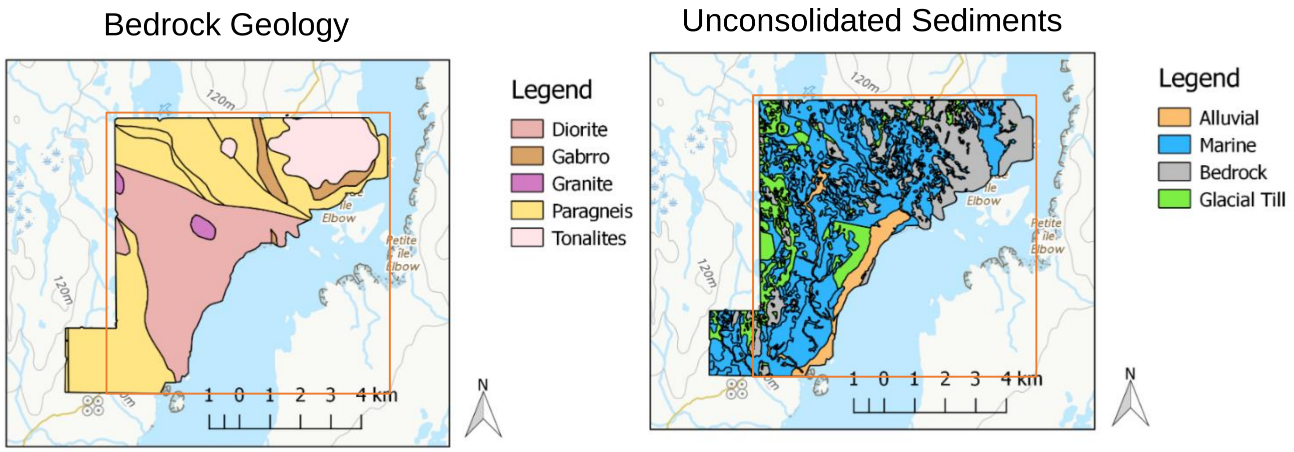


Figure 1. Kuujjuaq bedrock geology (left) and unconsolidated sediments (right). Orange box indicates the extent of the same area in Fig. 2.

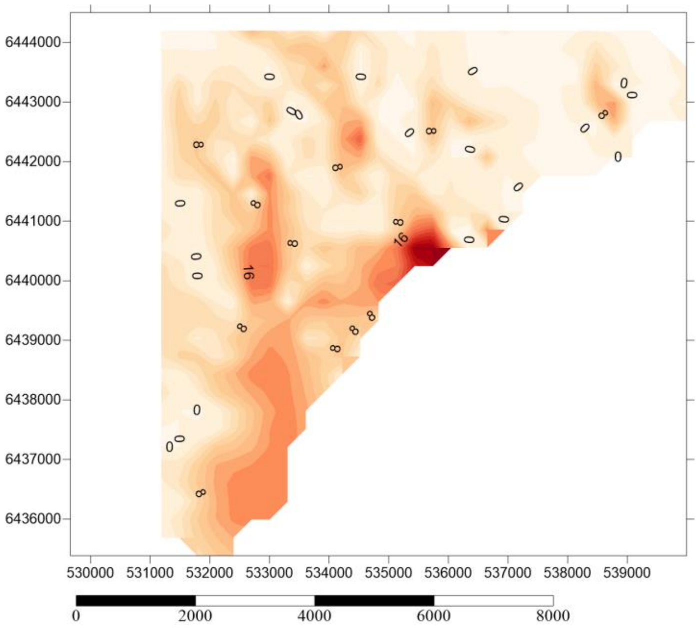


Figure 2. Depth of unconsolidated sediments in Kuujjuaq with bedrock outcrops colored white (labelled 0 m) and the deepest quaternary sediments colored dark red (30 m).

The ground thermal conductivity and heat capacity values for both unconsolidated sediments and bedrock geology were also incorporated to the layer. The weighted thermal conductivity and heat capacity were calculated for 100 m, 200 m and 300 m BHE lengths scenarios. A sample formula used to calculate the weighted thermal conductivity at 100 m BHE length is given as follow:

$$\lambda_{weighted} = \left(\frac{Depth_{unconsolidated}}{100}\cdot\lambda_{unconsolidated}\right) + \left(\frac{100-Depth_{unconsolidated}}{100}\cdot\lambda_{bedrock}\right) \quad (5)$$

The shallow geothermal potential of Kuujjuaq was calculated for each BHE length scenario by applying Equation 1.

2.2 Residential Building Heating Load

The heating load of a 252 m^2, one-floor residential house with 5 occupants was modeled with SIMEB, a software program that provides a simplified interface for the DOE-2 and Energy Plus calculation engines developed to perform building energy simulation, using weather data for Kuujjuaq and known parameters on residential buildings [3,25,26] (Table 3). In this paper, the DOE-2 algorithm was chosen as it is one of the most widely-used building energy modeling programs.

Since current data on building energy usage in Kuujjuaq is limited, hourly load profile data for a typical residential building in Anchorage, Alaska, US, with similar subarctic climate as Kuujjuaq, was initially used to calibrate the input parameters in SIMEB [27]. The building occupancy and usage schedule were adjusted until similar heating load profiles were achieved [28].

Table 3. Main SIMEB input parameters to simulate a typical residential building heating load in Kuujjuaq.

Parameter	Values	Reference
Thermal envelope		
Roof insulation	9 RSI	[28]
Wall insulation	5.11 RSI	[28]
Fenestration	U: 2.16 $W/m^2 K$ SHGC: 0.5	[28]
Domestic hot water maximum load	20.7 W/m^2	[48,49]
Central HVAC System		
Type	Single zone: single supply duct system	
Cooling	None	
Regulation		
Minimum temperature	21.1 °C	[27]
Maximum temperature	24.4 °C	
Perimeter heating	Hydronic baseboard	
Occupation		
Sensible heat	64.5 W/occupant	[27]
Latent heat	48.1 W/occupant	

2.2.1 Building Heating Scenarios and Efficiencies

The building heating systems considered in this study are summarized in Figure 3.

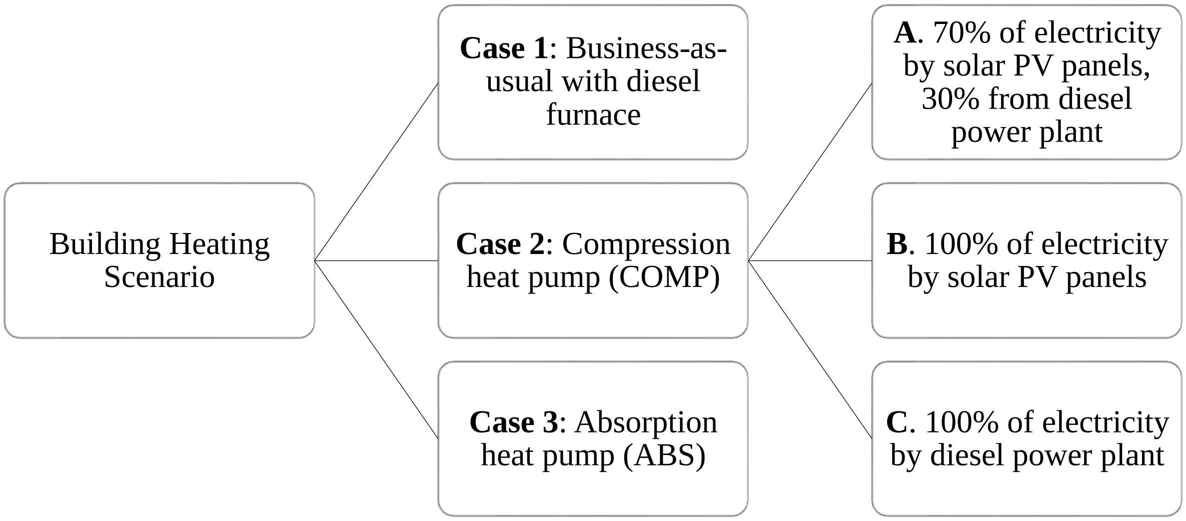


Figure 3. Building heating scenarios.

Both COMP and ABS can provide heating and cooling in building applications. However, COMP runs on electricity to extract geothermal energy, while ABS runs on thermal input, most commonly natural gas. Since diesel is readily available in Kuujjuaq, it is assumed the ABS described in Case 3 will be customized to run on diesel. The efficiencies of COMP and ABS are measured in coefficient of performance (COP) and gas utilization efficiency (GUE), respectively, and depend on the entering water temperature (EWT), which is defined as the temperature of fluid entering the heat pump. In turn, the EWT depends on both the BHE configuration and T_0. In this paper, the EWT was assumed to be equal to T_{lim} at -5°C. COP and GUE are the ratio of the heating supplied to the building to the electrical energy or, in the case of ABS, gas consumed by the compressor. For simplicity, the term COP will be used in this paper to refer to the efficiency of both COMP and ABS. The COP ratings of COMP are typically higher than ABS [28]. The COMP selected for this paper has a COP of 3.1, while the ABS has a COP of 1.2 at the selected EWT [31,32]. In comparison, the efficiency of diesel furnace considered in this paper is 78% or 0.78.

Electricity produced by the local diesel power plant is not advised to be used for building heating in Kuujjuaq since it is generated from a diesel power plant at an efficiency of 33.2%, which would lead to much higher subsidies and insufficient nominal capacity of the power plant to cover winter peak demand [32]. Therefore, Cases 2A and 2B consider the generation of electricity from solar photovoltaic (PV) panels.

Sizing a GCHP to provide all the heating required by a house is not normally recommended. The occasional peak heating load during severe weather conditions are usually met by a secondary heating system. Hence, for both Cases 2 and 3, GCHP is sized to meet 50% of the peak load. The remaining load is assumed to be covered with a diesel furnace.

2.2.2 Building Energy Consumption

Based on the simulated total annual building heating load in Kuujjuaq (Table 6), the energy consumptions for each heating scenario and for different heating equipment were calculated according to their efficiencies (or COPs) and energy densities [33] as follows:

1. 1 kWh electricity = 0.0036 GJ
2. 1 l diesel oil = 0.0387 GJ

2.2.3 BHE Drilling Length

Based on the average geothermal potential in Kuujjuaq ($\bar{Q}_{\mathrm{BHE}}$), the thermal energy available per meter drilled ($E_{\mathrm{g\ available}}$) were calculated for Cases 2 and 3 based on three BHE lengths (L) considered in the G.POT calculation.

$$E_{\mathrm{g\ available}} = \frac{\bar{Q}_{\mathrm{BHE}}}{L} \tag{6}$$

Based on the total ground load (E_{g}), which is the ground thermal energy required to meet the building load with the GCHP system, the total drilling length necessary (L_{drill}) can be calculated as follow:

$$L_{\mathrm{drill}} = \frac{E_{\mathrm{g}}}{E_{\mathrm{g\ available}}} \tag{7}$$

2.2.3 Solar Panels Quantity

The number of solar panels required (N_{s}) in Scenarios 2A and 2B were calculated by dividing the electricity demand to be met by the solar panels (E_{s}) by the energy generated from each panel ($E_{\mathrm{s\ available}}$). $E_{\mathrm{s\ available}}$ was calculated by multiplying the solar panel rating, which was assumed to be 0.3 kW with 1,033 kWh/kW/year, the solar PV potential in Kuujjuaq [34].

$$N_{\mathrm{s}} = \frac{E_{\mathrm{s}}}{E_{\mathrm{s\ available}}} \tag{8}$$

2.3 Life-Cycle Cost Analysis

2.3.1 Costs of Heating System

All costs in this study are in Canadian dollars (CAD), unless otherwise specified. For prices involving United States dollars (USD), the conversion rate 1 USD = 1.272 CAD on November 6, 2018 was considered [35]. A 14.98% Québec sales tax was applied to all costs. The total cost (C_{t}) was divided to capital costs (C_{c}), annual costs (C_{a}), and periodic costs (C_{p}; Eq. 9). Capital costs include the cost of equipment, installation or labor and shipping. Annual costs include the costs of energy (diesel and/or electricity), maintenance and GHG or carbon dioxide (CO_2) emissions. Periodic costs include cost of equipment replacement at the end of its lifetime, installation and shipping.

$$C_{\mathrm{t}} = C_{\mathrm{c}} + C_{\mathrm{a}} + C_{\mathrm{p}} \tag{9}$$

Price of fuel: Diesel price in Kuujjuaq is \$2.03/l before and \$1.63/l after subsidy [1]. Cost of electricity production by diesel power plant in Kuujjuaq is \$0.86/kWh [6]. With subsidy, the base rate for electricity is 40.64c/day, in addition to \$5.40/month in the summer and \$6.21/month in the winter, while the variable rate is 5.91c/kWh for the first 10,950 kWh per annum and 41.05c/kWh thereafter [36].

Price and lifetime of equipment: Prices are summarized in Table 4.

Table 4. Price and lifetime of equipment used in the life-cycle cost analysis.

Item	Lifetime (years)	Costs (\$)	Comments and Source
Oil tank	25	666.92	[37]
Boiler	15	3,248.30	[38]
COMP and ABS	20	9,480.00	Assumed price for 35 kW models, which can cover the heating needs of three houses
Drilling	50	344.94	Cost per meter, includes labor and u-pipe heat exchanger [39]
Solar panel	20	5.00	Price includes labor for installation [40]

Labor wage and installation time: An average wage for 13 maintenance and technician jobs in Kuujjuaq was \$26.32 [41]. It takes two working days for boiler installation and one working day for tank installation. Due to the difference in expertise required, the average wage for heat pump installation is assumed to be \$35.00. Heat pump installation takes two working days.

Maintenance: Maintenance for all heating scenario is assumed to be conducted annually at \$3.87/m^2 for diesel furnace system and \$1.81/m^2 for both heat pump systems [42]. Since in Cases 2 and 3 diesel furnaces is only used to meet 50% of the peak heating demand, the maintenance cost for oil furnace in these cases were halved and added to the heat pump maintenance cost.

Shipping: Shipping of oil tank, oil furnace and heat pumps from Québec City is provided by NEAS cargo shipping company at approximately \$1.15/kg, which includes tax and fuel surcharge [43].

Equipment weight: A 275-gallon oil tank weighs 127 kg. The average weight of seven oil furnaces is 255 kg. The weight of COMP is 316.6 kg [30]. The weight of ABS is 300 kg [31]. The weight of wooden pallet packaging for each equipment was assumed at 15 kg. The weight of solar panel was assumed at 15 kg/m^2, while a typical size of a solar panel is 1.64 m^2.

2.3.2 Cost of CO_2 Emissions

The CO_2 emissions per MJ of product of six heating oil companies in North America were averaged and multiplied by the annual diesel consumption to determine the annual carbon dioxide emissions for each heating scenario [44].

The CO_2 emissions for each scenario was multiplied with $19.40/t, the estimated price of carbon in Québec's carbon market in 2020, to obtain the cost of CO_2 emissions associated with each heating option [45].

2.3.3 Net Present Cost and Sensitivity Analysis

A net present cost (NPC) approach was chosen to compare the 50-years life-cycle costs (LCCs) of the heating alternatives. The NPC formula discounts costs incurred at different time point (n) during the project life-cycle, at the discount rate (*r*) to a common point in time, which in this study is 2020. In other words, the NPC formula allows all future numbers to be translated in terms of present value to allow logical comparison. However, the LCCs were not adjusted with inflation and with other factors as doing so for such long-term calculations could potentially introduce cumulative error. NPC calculations were applied to obtain the LCC for both home-owner and government.

$$NPC = \sum_{n=0}^{N} \frac{C_{\mathrm{t,n}}}{(1+r)^{\mathrm{n}}} \tag{10}$$

To address the uncertainty in predicting these costs, sensitivity analyses were conducted to measure the effect of each input variable to the NPC. Key variables selected for sensitivity analysis were capital cost, energy cost, maintenance cost, and periodic costs for heat pump, oil boiler, oil tank and solar panels. Each variable was changed by 30%, with 10% increments above and below their original values and sensitivity graphs were plotted for each heating scenario to visualize the changes in NPC. The line gradient indicates the sensitivity of the NPC to changes in each variable. A steeper slope indicates a greater effect on the NPC.

2.3.4 Revenue from Selling in Commodity Market

Switching from business-as-usual heating scenario in Case 1 to GCHP heating systems in Case 2 and 3 cuts the consumption of diesel. This opportunity benefit is defined as the revenue gained from selling surplus diesel in the commodity market and the avoided cost for not shipping and selling to Kuujjuaq. These costs were considered when calculating the NPCs of Cases 2 and 3. The cost of diesel was assumed to be USD$1.41/gal or $0.47/l based on the price of RBOB gasoline in the commodity market on January 5, 2019 [46]. The cost of shipping diesel was assumed to be the cost of diesel production before subsidy minus the cost after subsidy at $0.40/l.

2.3.5 Economic Scenarios

In order to propose recommendation and identify areas for future improvement, the LCCAs were applied for various economic scenarios, where one to several variables were varied, while the others were held constant (Table 5). The first scenario is based on current condition and costs assumed above, while the second scenario show the uncertainties resulting from best ($50/m), moderate ($175/m) and worst ($300/m) BHE drilling costs. The cost of drilling was assumed to be the same for drilling in both bedrock and quaternary deposits in Kuujjuaq. In a more competitive market, the drilling cost tend to be more variable. However, in such a remote region, there is limited drilling service providers that the cost tends to be fixed and high. The worst-case drilling cost was assumed based on a requested quote from a drilling company in Kuujjuaq, while the best-case drilling cost was assumed based on the typical BHE drilling cost in the south [39]. In the third and fourth economic scenarios, the effect of government incentive to the NPC can be observed, whereas the first and second economic scenarios provide an overview of the total costs of the project.

Table 5. Summary of the economic scenarios used to calculate the LCCs.

Economic Scenario	**Drilling**		**Energy (Diesel and Electricity) Subsidy**	**GCHP and Solar Panel Costs Covered by the Government**
	Cost ($/m)	**Cost Covered by the Government**		
1	300	no	yes	no
2	300, 175 and 50	no	yes	no
3	300	50%	no	50%
4	50	no	no	50%

2.3.6 Assumptions

In addition to the costs and economic scenarios stated above, the following technical assumptions were made:

1. Solar PV panels were installed south facing at an angle equal to the latitude, with no shade, such as from buildings, trees and snow.
2. Cost of solar energy storage was not considered.
3. Cost of heating distribution was not considered to limit the scope of the economic analysis.
4. Tools and parts, such as bolts and screws were considered negligible and not included.
5. Roof replacement costs incurred when solar PV panels are replaced were not considered as they need to be replaced regardless.

The following economic assumptions were made:

1. Discount rate = 6% [47].
2. Annual energy and maintenance costs escalation rates = 0%.
3. Project lifetime = 50 years.
4. Project starts in 2020 and ends in 2069.
5. No sudden fluctuation in the costs of electricity and diesel throughout the project life-cycle.
6. Depreciation rates of heating equipment not considered.
7. In the third, fourth and fifth economic scenarios, the government is assumed to bear the cost of CO_2 emissions.

3. RESULTS

3.1 Shallow Geothermal Potential Maps

The shallow geothermal potential $\bar{Q}_{BHE}$, calculated using the G.POT equation (Eq. 1) and the input parameters described in Tables 1 and 2, show heat extraction potential varying with the local geology and the ground temperature or depth of three BHE lengths in Kuujjuaq (Figure 4).

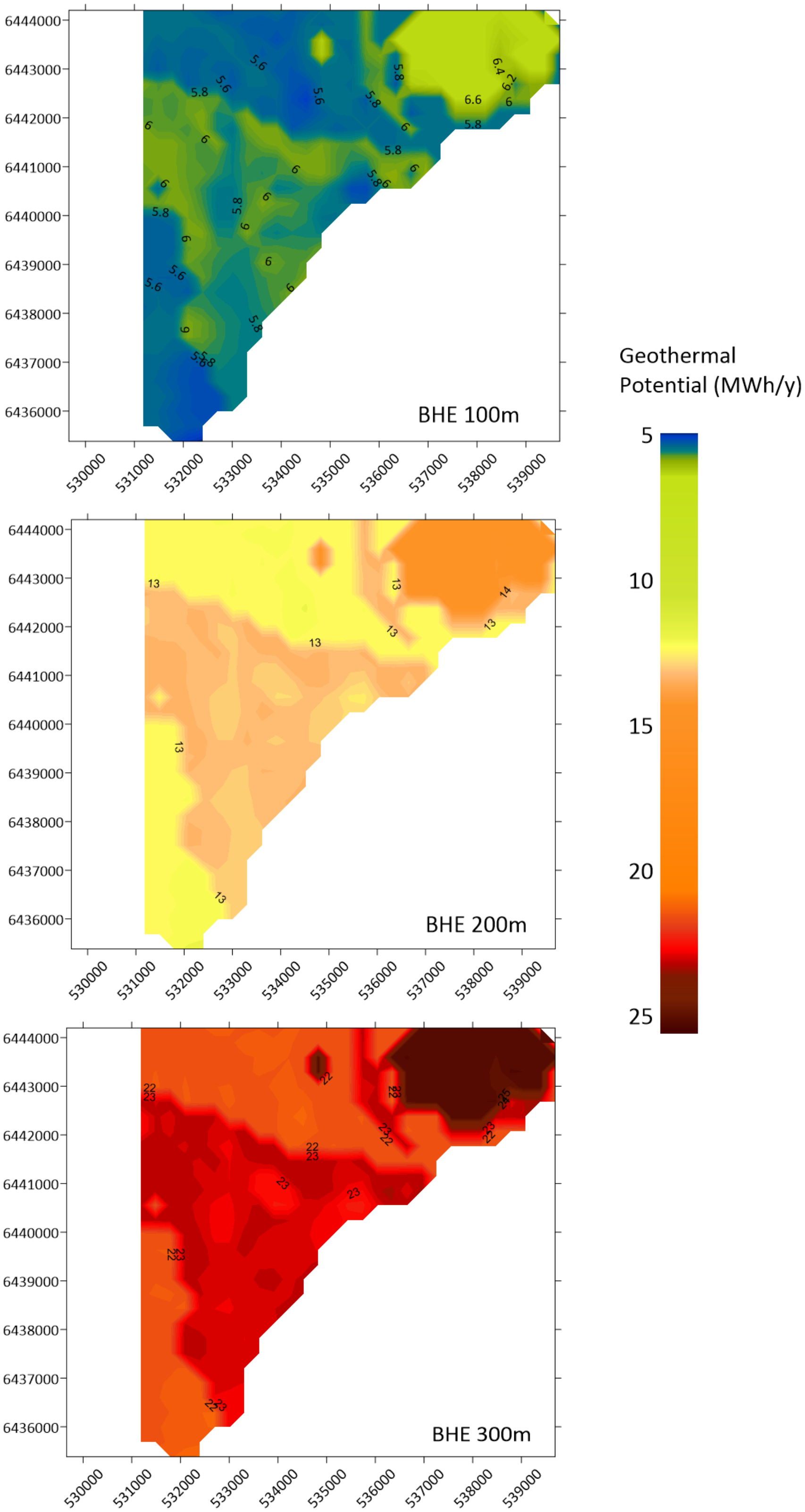


Figure 4. Geothermal potential maps of Kuujjuaq based on three BHE lengths of 100 m (top), 200 m (center) and 300 m (bottom). X and Y axes represent map coordinates (NAD83/UTM Zone 19N).

The geothermal potential at 100 m BHE length ranged 5.2-6.6 MWh/year and averaged 5.8 MWh/year. At 200 m, the geothermal potential ranged 12.2-14.9 MWh/year and averaged 13.3 MWh/year. At 300 m, the geothermal potential ranged 21.3-25.6 MWh/year and averaged 22.9 MWh/year. Thus, the geothermal potential increases supralinearly with borehole lengths due to higher temperature at greater depths and lower thermal conductivity of shallow quaternary deposits.

Geologically-accurate geothermal potential maps were successfully produced from field observations and laboratory measurements of thermal properties. In areas where the dominating bedrock lithology has lower thermal conductivity, there is generally lower geothermal potential in the area, and vice versa. For instance, in the area overlying paragneiss bedrock, which has an average thermal conductivity of 2.7 W/mK, there is lower geothermal potential. While in area that overlies the tonalites, which has an average thermal conductivity of 3.4 W/mK, there is higher geothermal potential (Table 1).

3.2 Residential Building Heating Load

Based on Kuujjuaq's weather data and the building parameters described previously, the annual heating load of a 252 m^2 residential building in Kuujjuaq is 71,343 kWh. Figure 5 shows the daily heating load profile modelled using SIMEB.

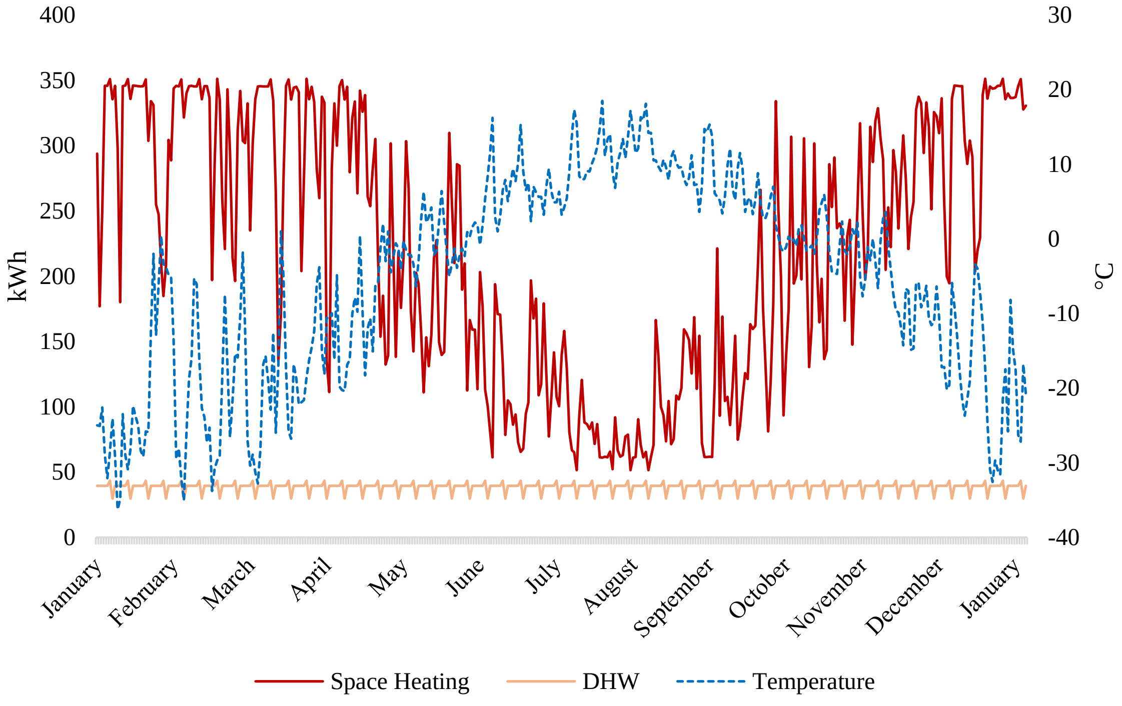


Figure 5. Average daily temperature and heating load profile of a typical residential building in Kuujjuaq.

3.2.1 Building Energy Consumption

The energy consumptions for each heating equipment scenario (Fig. 3) were calculated based on the building heating load, the efficiency or COP of the heating equipment and the energy densities (Table 6). For the business-as-usual heating scenario (Case 1), this translates to an annual energy consumption of 8,174.7 l or 32.4 l/m^2. This value is comparable to the reported annual average energy consumption of 3,100 l diesel for a 110.9 m^2 house in Kuujjuaq, which translates to an energy consumption of 28.0 l/m^2 [12].

Table 6. Energy consumption breakdowns for different heating equipment scenarios.

Heating Scenario	Diesel furnace	GCHP			
	Diesel (l)	Electricity from solar PV panels, E_s (kWh)	Diesel for GCHP (l)	Ground thermal energy, E_g (kWh)	Electricity from diesel power plant (kWh)
1	8,174.7	0	0	0	0
2A	4,253.1	8,054.9	0	2,4164.6	3,452.1
2B	4,253.1	11,506.9	0	2,4164.6	0
2C	4,253.1	0	0	2,4164.6	11,506.9
3	4,253.1	0	2,764.5	5,945.3	0

3.2.2 BHE Drilling Lengths

Based on the average geothermal potential in Kuujjuaq at different BHE lengths, the annual thermal energy that can be extracted ($E_{g\ \mathrm{available}}$) were 58.4 kWh/m for 100 m BHE, 66.3 kWh/m for 200 m BHE and 76.3 kWh/m for 300 m BHE. The drilling lengths (L_{drill}) for each type of heat pump were then calculated according to the required thermal energy from the ground (E_g). For Case 2, the $E_{g\ \mathrm{available}}$ from a 300 m BHE was considered due to the high E_g, while the $E_{g\ \mathrm{available}}$ from a 100 m BHE was used in Case 3. Based on this, the drilling lengths required in Cases 2 and 3 were 316.5 m and 101.8 m, respectively.

3.2.3 Solar Panels Quantity

The energy generated by each solar PV panel ($E_{s\ \mathrm{available}}$) was calculated to be 309.9 kWh/year, despite the perception that there would be insufficient solar energy in the north. The number of solar PV panels required (N_S) for Case 2A is 26 panels and for Case 2B is 37 panels.

3.3 Life-Cycle Cost Analysis

The average CO_2 emission considered and determined from six heating oil companies is 0.0902 tCO_2/GJ. The cost of emission was then obtained by multiplying this value with the price of carbon and included in the NPC calculations.

3.3.1 Economic Scenario 1

The results of the 50-years LCCA based on the current condition and values outlined previously are shown in Table 7. In this economic scenario, it is interesting to note that a linear trend between CO_2 emissions and NPC could also be observed; the heating option emitting higher CO_2 has higher 50 years total NPC (Fig. 6). Despite the high initial capital costs incurred in Cases 2A and 2B, the low annual costs combined with the high annual opportunity benefit make COMP with solar panels the most economically attractive building heating solution that also reduces CO_2 emissions. Cases 2A and 2B are expected to have a payback period comparable to the business-as-usual scenario within 11 and 12 years, respectively, and hence can be considered fast for such major investment.

Table 7. Summary of costs, cost of CO_2 emissions, and NPCs of 50-years LCC for business-as-usual and alternative heating scenarios.

Heating Scenario	**Capital Cost ($)**	**Annual Costs ($)**		**Periodic Cost ($)**	**Parts Replaced**	**Annual Opportunity Benefit ($)**	**CO_2 Emissions (t)**	**Annual Cost of Emission ($)**	**Total NPC ($)**
		Energy	**Maintenance**						
1	5,063	16,595	1,059	1,041 4,022	Diesel tank Diesel furnace	0	28.5	554	276,875
2A	158,324	8,634	849	4,354 1,041 4,022 39,723	Heat pump Diesel tank Diesel furnace Solar PV panel	9,819	18.0	350	203,153
2B	175,348	8,634	849	4,354 1,041 4,022 56,747	Heat pump Diesel tank Diesel furnace Solar PV panel	9,819	14.8	288	179,433
2C	118,601	18,530	849	4,354 1,041 4,022	Heat pump Diesel tank Diesel furnace	9,819	25.5	495	258,500
3	44,484	14,246	849	4,335 1,041 4,022	Heat pump Diesel tank Diesel furnace	2,897	24.5	475	231,459

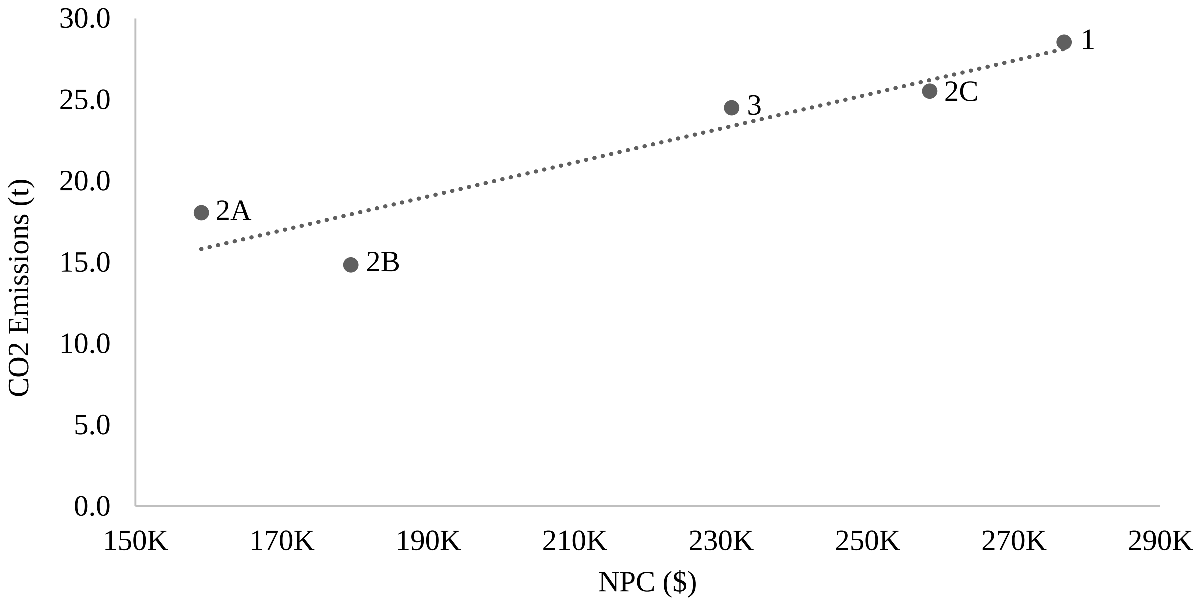
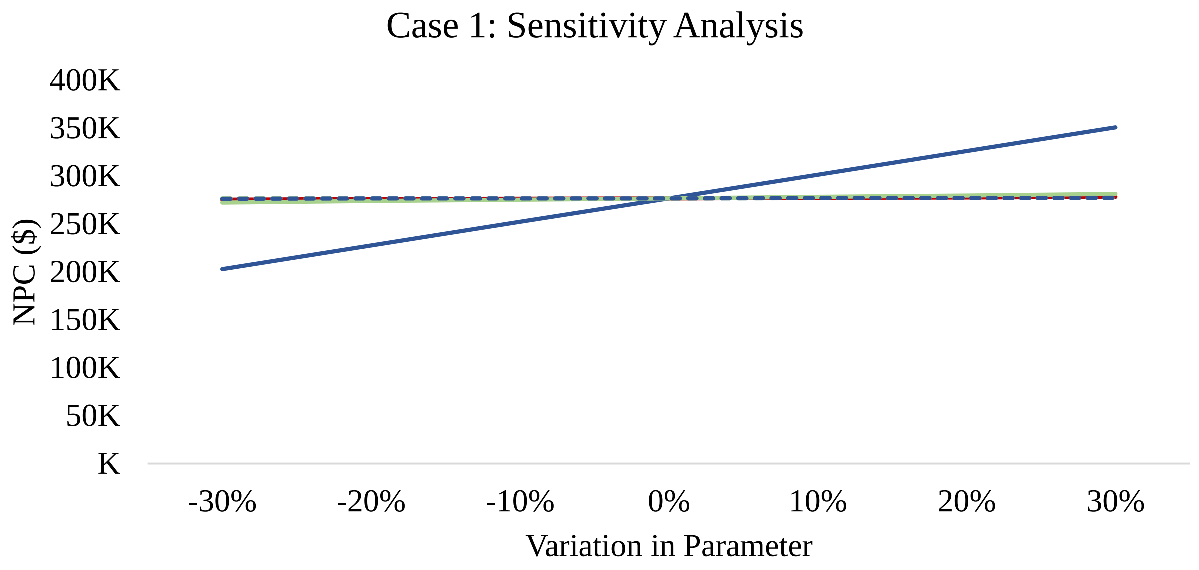
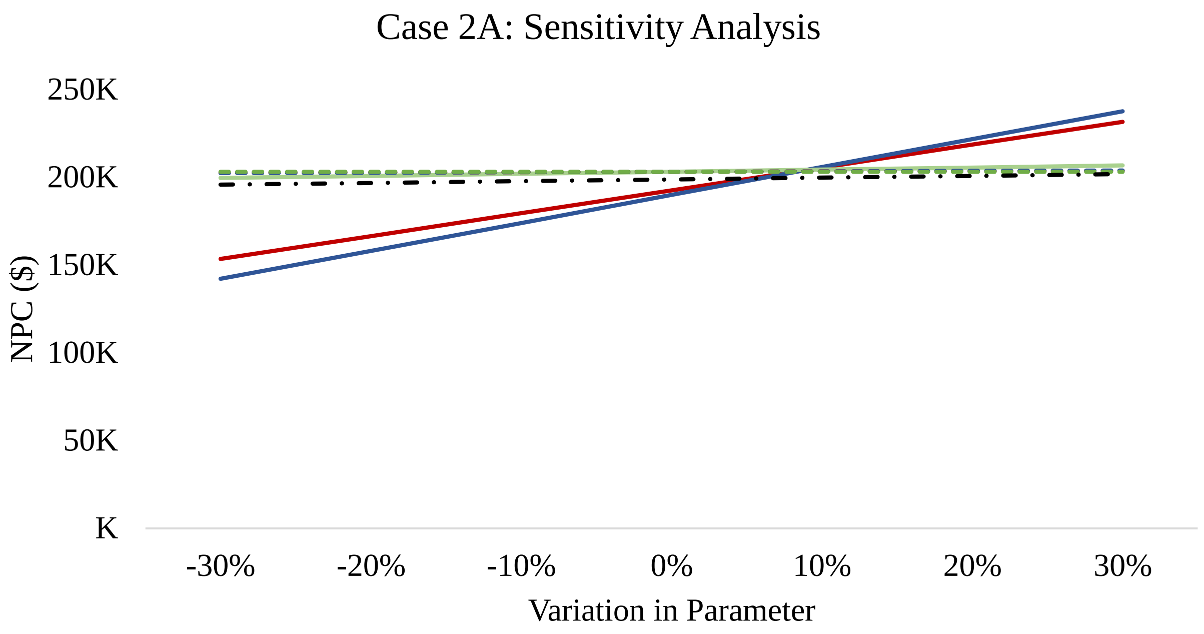
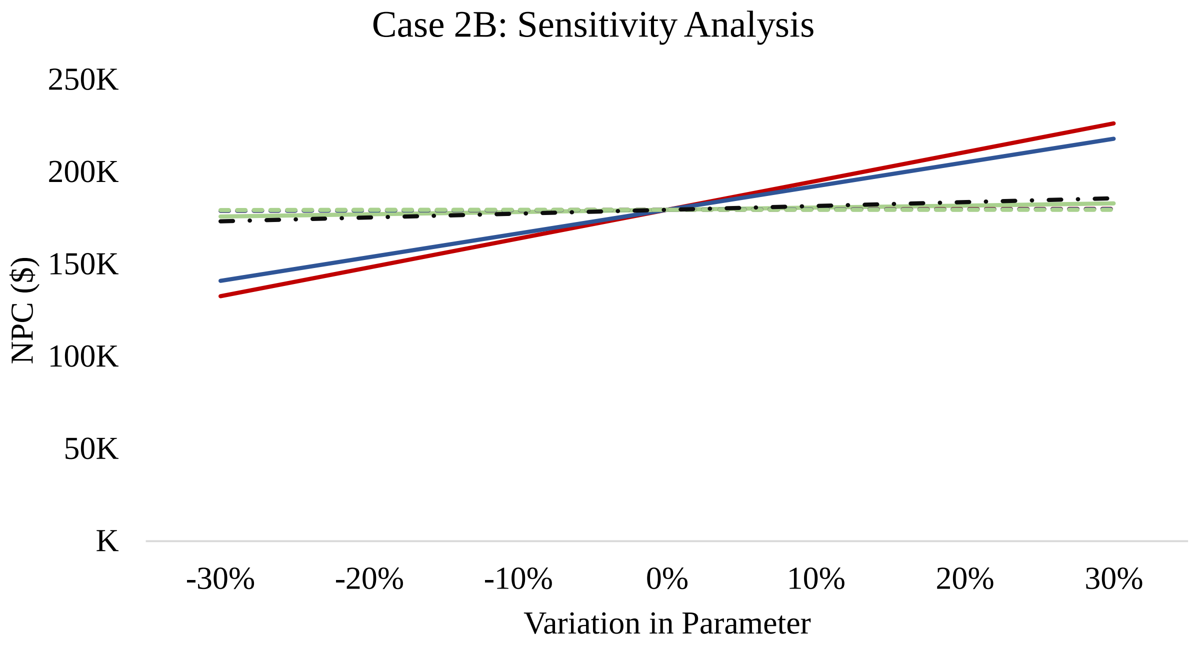


Figure 6. NPC vs. CO_2 emissions of different building heating scenarios.

Sensitivity analyses of key inputs reveal that the most sensitive cost item for all heating equipment were either the energy cost or capital cost (Fig. 7). Variations on the periodic costs and maintenance cost appear to have little effect on the NPC of the LCC of the heating options. The energy cost is more sensitive than the capital cost for heating options that rely heavily on diesel fuel, (Cases 2C and 3). For these last options, the high energy cost, which is heavily influenced by the transportation cost to the north, affects the NPC more than the capital cost, which includes the cost of the heating equipment and BHE drilling in the case of GCHP heating.


Case 1: Sensitivity Analysis


Case 2A: Sensitivity Analysis
250K
200K
150K
100K
50K
K
NPC ($)
-30%
-20%
-10%
0%
10%
20%
30%
Variation in Parameter


Case 2B: Sensitivity Analysis
250K
200K
150K
100K
50K
K
NPC ($)
-30%
-20%
-10%
0%
10%
20%
30%
Variation in Parameter

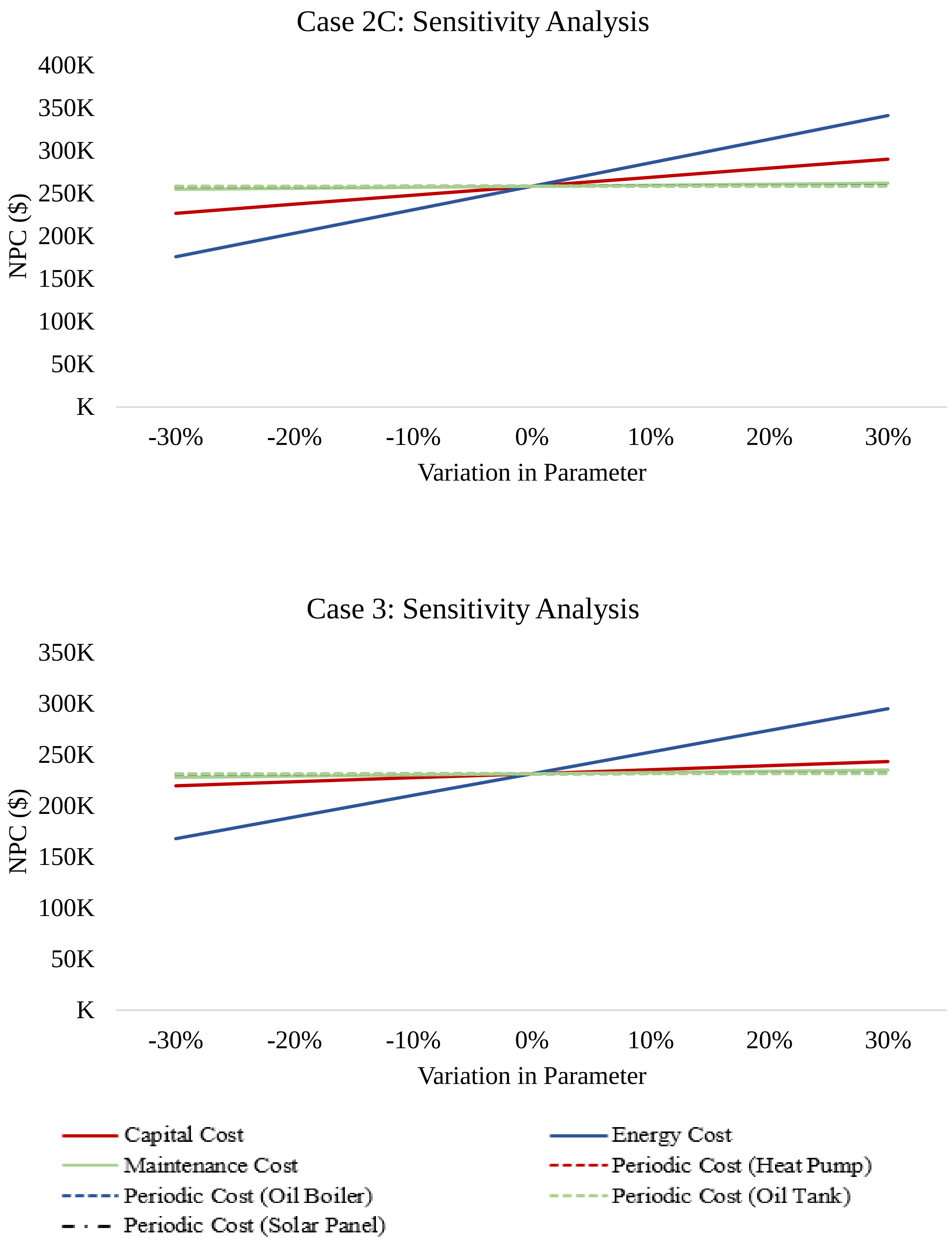


Figure 7. Sensitivity analyses of key parameters in all building heating options based on Economic Scenario 1.

3.3.2 Economic Scenario 2

In this economic scenario, LCCs for the heating options were calculated based on three drilling costs (Fig. 8). Regardless of the drilling costs, switching to any type of GCHP seem to always be more economically attractive and will payback relatively fast within the lifetime in respect to the business-as-usual scenario. Cases 2A and 2B present the largest savings from the business-as-usual scenario. With the best drilling cost at $50/m, the paybacks for these two cases are expected to significantly decrease to within 3 and 4 years, respectively. Thus, a policy to support the growth of drilling industry to lower drilling cost in the north could be beneficial, especially when considering a COMP as an alternative heating system in Kuujjuaq.

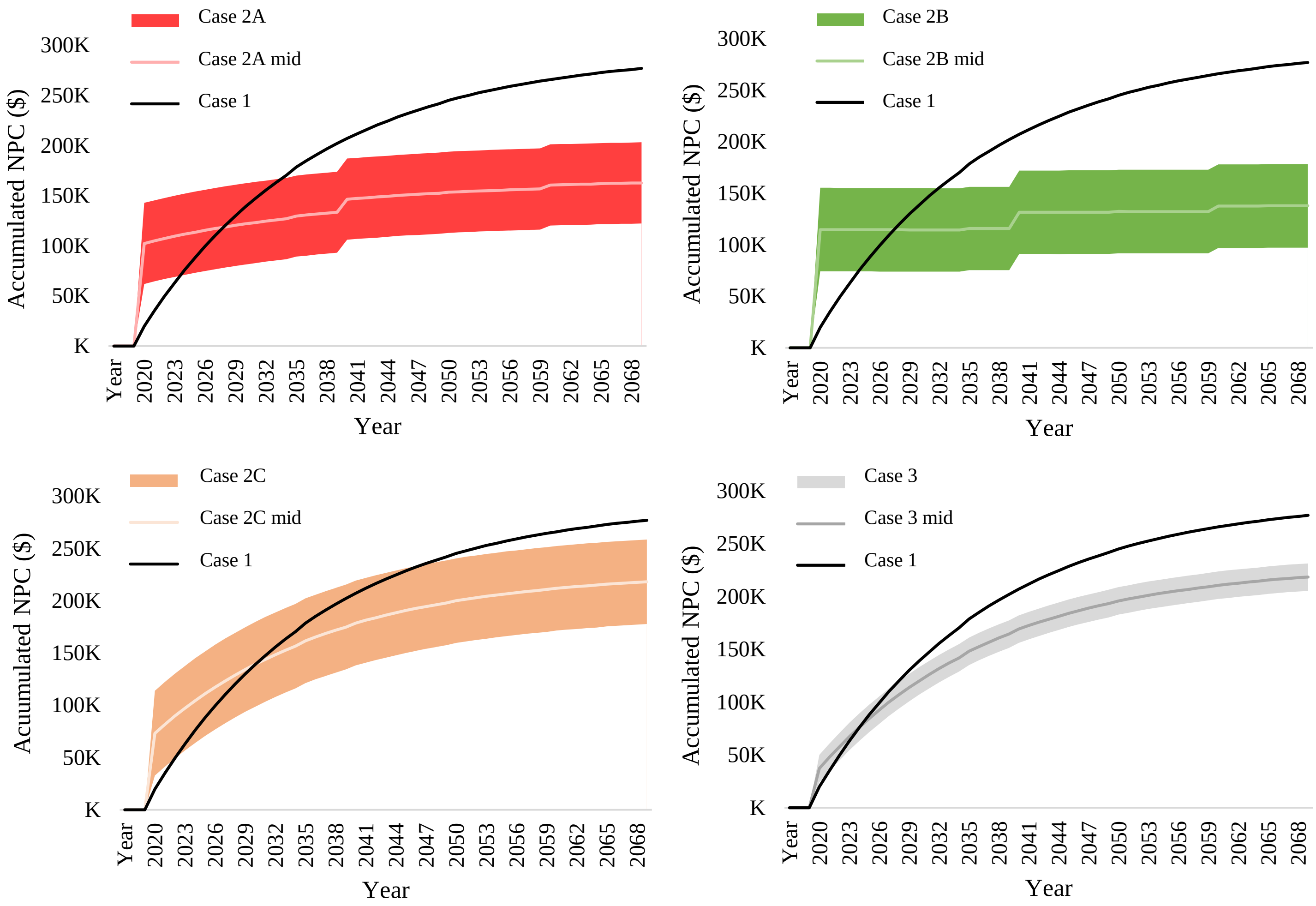


Figure 8. Range of accumulated NPCs based on worst to best BHE drilling costs compared to that of business-as-usual heating scenario (case 1).

3.3.3 Economic Scenario 3

The purpose of this analysis is to calculate a scenario in which home-owners are encouraged to switch to GCHP system. Additionally, while the total NPCs remain the same for all cases as in Economic Scenario 1, this scenario helps to see the breakdown of burden for home-owner and government. Due to the high cost of fossil fuel in Kuujjuaq, any heating option that consumes more fossil fuel, such in Cases 1, 2C and 3, results in more uneven distribution of costs between home-owner and government, with a higher proportion of the burden falling on the hands of the home-owner (Table 8).

Table 8. Total 50 years NPCs for home-owner and government based on Economic Scenario 3.

Heating Scenario	**Total NPC for Home-Owner ($)**	**Total NPC for Government ($)**
1	268,646	8,232
2A	149,941	53,211
2B	116,471	62,962
2C	228,039	30,460
3	214,783	16,676

3.3.4 Economic Scenario 4

Previous sensitivity analyses (Fig. 7) have shown that energy cost and capital cost are the most sensitive cost item in Cases 2A and 2B. The purpose of this economic scenario is to analyze the effect of eliminating subsidy on diesel and electricity and lower BHE drilling cost in the north to shed light at the potential of GCHP as an optimum building heating solution in northern remote communities that can reduce both costs and CO_2 emissions.

Although Case 2C brings profit to the government, the cost to the home-owner is high (Table 9). Business-as-usual and Case 3 are not the most viable due to the high costs incurred to the home-owner. Again, Cases 2A and 2B have the lowest total NPCs and hence, are more economically attractive compared to the business-as-usual and other heating options. Additionally, this economic scenario results in lower total NPCs for all GCHP heating (Cases 2 and 3) as compared to Economic Scenario 1, which analyses NPCs based on the current conditions. This means that the development of northern drilling industry and such government incentive are predicted to be efficient in reducing total LCCs for any GCHP systems listed in this paper.

Table 9. Total 50 years NPCs for home-owner and government based on Economic Scenario 4.

Heating Scenario	**Total NPC for Home-Owner ($)**	**Total NPC for Government ($)**
1	268,646	8,232
2A	117,550	4,625

2B	84,080	14,375
2C	195,648	-18,126
3	204,369	1,055

Both Cases 2A and 2B utilizes the COMP as the main heating equipment, the only difference being the proportion of electricity that comes from solar PV panels. Increasing the proportion of electricity coming from solar PV panels reduces the cost of heating for the home-owner more than it increases for the government (Fig. 9). Additionally, when all electricity required for the COMP comes from solar PV panels, the total combined NPC for both government and home-owner, and CO_2 emissions become lower than other proportions. Below 56%, COMP is most economically attractive for the government, as the government would have a negative total NPC, which means positive cashflow or revenue through selling surplus diesel in the commodity market. It is also economically attractive for home-owner. However, it is important to note that the total NPC for home-owner decreases as the proportion of electricity increases. At 56% the government breaks even as the total NPC becomes zero. At 80%, the total NPC for COMP equals the total NPC for business-as-usual or diesel furnace heating scenario. Above 80%, COMP becomes a less economically attractive heating option compared to diesel furnace for the government, although it is still economically attractive for the home-owner. Thus, COMP is most economically attractive for both the home-owner and government alike when the proportion of electricity coming from solar PV panels is below 80%.

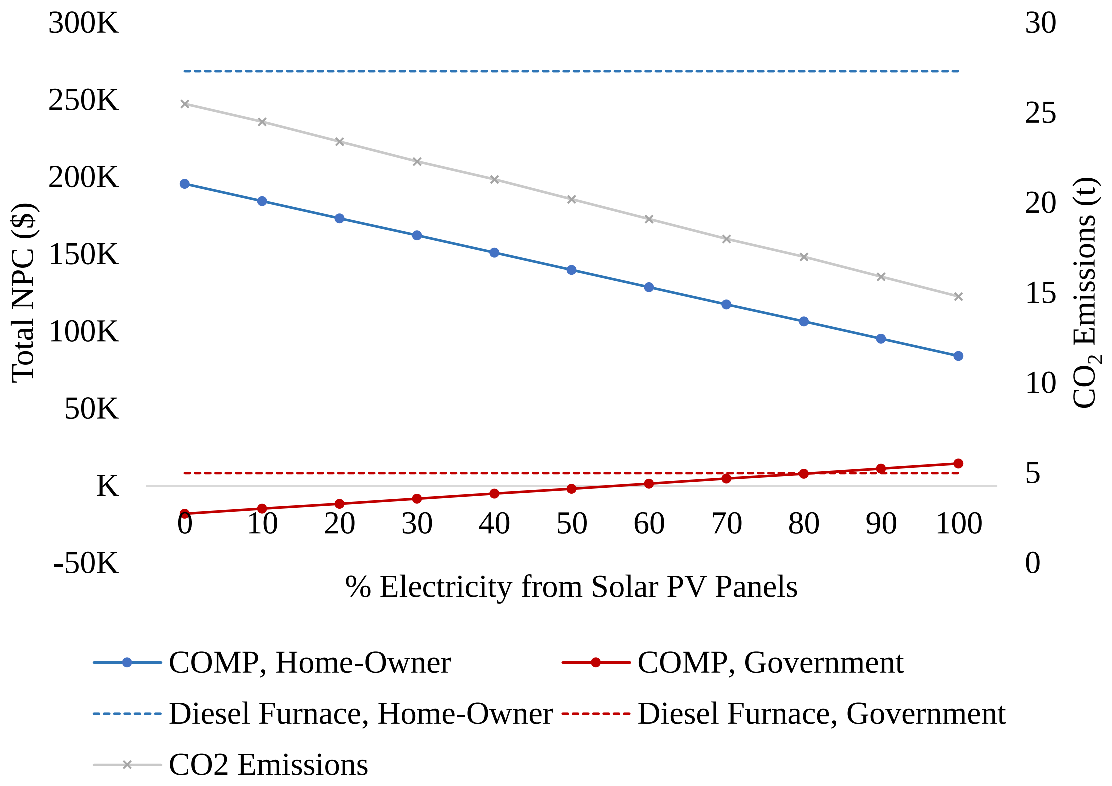


Figure 9. Optimization to determine the best proportion (%) of electricity coming from solar panels to run a COMP for building heating in Kuujjuaq.

4. DISCUSSION

In this study, the COPs of the GCHP systems considered were assumed to remain constant throughout the project's life-cycle, while in reality the COP would vary, albeit by little throughout seasons and years. This COP assumption is conservative since it is based on the minimum water temperature leaving the BHE for the 50-years period considered in the G.POT calculation. Additionally, since there is currently no GCHP being operated in remote northern communities with heating requirements above 8,000 HDD, the presented study is essential before moving towards first demonstration or pilot projects that can provide experimental data. Thus, further study on the performance of COMP and ABS operating in the area or in similar subarctic conditions would be required to produce a more accurate forecast and are anticipated to potentially improve the project cashflow. Additionally, the average annual solar PV potential in Kuujjuaq was used in calculating the number of solar panels required in the COMP heating scenario as a simplification, as a detailed solar analysis was beyond the scope of this study. Future study could hence, focus on the economics of using battery storage versus sizing the solar panels according to the monthly solar PV potential in Kuujjuaq. Moreover, social factors, such as acceptability and implementation effort were not considered and could be a subject of future research.

Consistent with the results from Pike and Whitney's study [12] in Alaska, heat pumps can be a viable heating technology for cold climates. The economic benefit of GCHP system, however, depends heavily on the costs of fuel and electricity in the area, and sensitivity analyses in this study demonstrated that the costs of energy form one of the most critical factors that influences the Kuujjuaq system's economic viability. In Alaska, although the costs of fuel oil and natural gas are relatively high, the cost of electricity is low [13]. For Kuujjuaq, a combination of solutions was considered and COMP with electricity from solar PV panels was found to be the most economically attractive option, as the costs of both fuel and electricity are high in this region. The energy cost of heating options relying on a greater diesel fuel proportion is less sensitive to capital cost. For this reason, the switch to renewable energy should be favored, not only for environmental reasons, but also for the economic savings obtained over the system operation. The cost of energy could thus be a tool that both governments and businesses use to simulate innovations and foster renewable energy utilization.

In addition to analysing the feasibility of ABS and COMP, the potential of COMP coupled with solar PV panels was explored. The feasibility of solar thermal collectors for heat generation, however, was not considered mainly because heat production mostly occurs during the relatively short summer, while heating is required year long. In a previous study, the use of solar thermal collectors with underground thermal energy storage was analyzed by Giordano and Raymond [50]. In their study, the five-year technical viability of underground thermal storage for heat production for drinking water was positively confirmed through detailed transient simulations. However, they pointed out that the efficiency of thermal collectors in such cold climates can be limited due to the high amount of anti-freeze needed to run the system, and that the use of PV panels can provide better overall performance as suggested by Bourbonnais and Déry [51].

Moreover, this study demonstrated that drilling cost is an important key factor for the development of GCHP systems in Kuujjuaq, as capital costs form the second most sensitive cost item (see Section 3.3.1). While Giordano et al. [18] defined \$150/m as a threshold drilling cost for GCHP to be of economic interest in the north, the detailed LCCA presented in this contribution revealed that over a 50-years period, GCHPs provide relevant paybacks compared to the current diesel-dependent situation even at the highest drilling cost considered (\$300/m, see Fig. 8).

Although previous studies have proven successful utilization of GCHP technology in various cold regions worldwide and the technical viability of shallow geothermal technology in the study area, none have studied the detailed economic feasibility in remote subarctic region [12-18]. This study attempted to address this gap. Furthermore, the G.POT method [19] was successfully applied to estimate the shallow geothermal potential in Kuujjuaq, enabling a long-term prediction of GCHP economic performance in such climate and community. Finally, this study proposed a viable alternative to building heating in Kuujjuaq by using COMP with electricity derived from solar panels, thereby providing a solution to help this community achieve energy security and independence using a locally generated and sustainable resource.

5. CONCLUSIONS

Presently, Nunavik's remote northern communities are heavily dependent on fossil fuel to meet their heating demands, which incurs high costs, energy dependence and net CO_2 emissions. This study focused on the economic attractiveness and emissions reduction potential of ground-coupled heat pump (GCHP) as an alternative heating source. Although it is powered by either electricity or a heat source, the main advantage of GCHP lies in its ability to supply more energy than that used to operate it. Furthermore, the methods listed was applied for a case study in Kuujjuaq, the regional capital of Nunavik. However, the same workflow can be useful to quantify the shallow geothermal resources and the economical feasibility of the GCHP technology implementation for any study area. The heating options analyzed in this study were:

1. **Case 1:** Business-as-usual using diesel furnace
2. **Case 2A:** Compression GCHP with 70% of electricity derived from solar photovoltaic (PV) panels and 30% from diesel power plant
3. **Case 2B:** Compression GCHP with 100% of electricity derived from solar PV panels
4. **Case 2C:** Compression GCHP with 100% of electricity derived from diesel power plant
5. **Case 3:** Absorption GCHP customized to run on diesel

The conclusions of this study can be summarized as follow:

1. Maps of the shallow geothermal potential of Kuujjuaq showed a relatively high potential for such cold region, ranging between 5.8 MWh/year and 22.9 MWh/year, and that it increases more than linearly with borehole depths (Fig. 4).
2. 50-years life-cycle cost analysis based on current costs and conditions (Economic Scenario 1) revealed that all GCHP options are economically more attractive compared to the diesel furnace heating. However, compression GCHP with electricity from solar panels (Cases 2A and 2B) presents the most efficient, environmentally friendly and cheapest option at a 50-years net present cost of $179,433, compared to diesel furnace option at $276,875. The total predicted costs were even lower in Economic Scenario 4 when the cost of BHE drilling was reduced to $50/m (similar to the cost in the south) and government provides incentive by covering 50% of GCHP and/or solar panels costs, while energy subsidies are eliminated and home-owner fully responsible for the drilling cost. In this scenario, the compression heat pump option costs as low as $84,080 for the home-owner and $14,375 for the government, while the diesel furnace option costs $268,646 for home-owner and $8,232 for the government.
3. Consistent with the results of previous studies [12,13], energy and capital costs form the most sensitive cost items for all heating options
4. The higher the proportion of electricity derived from solar panels, the lower the predicted costs for compression GCHP heating option. However, 80% was determined to be the maximum cut-off for this technology to be the more attractive heating solution compared to diesel furnace for both the government and home-owner. The optimum proportion depends on factors such as governmental budget, availability of grants and capital.

As with any development project, without the appropriate government policy to support the northern drilling industry or incentive to alleviate the cost burden from the hands of the home-owner, it could be a challenge to initiate such project, especially since there is currently a lack of local expertise to install borehole heat exchanger and geothermal heat pump systems in Nunavik. Nevertheless, given a suitable human resource capacity, compression GCHP with a proportion of electricity derived from solar PV panels remains the most economically attractive heating solution that offsets CO_2 emissions based on the conditions listed in this study.

DECLARATION OF INTEREST

None

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LIST OF SYMBOLS

Symbols

C_a	Annual cost ($)
E_t	Annual energy output (kWh/year)
L	Borehole length (m)
r_b	Borehole radius (m)
R_b	Borehole thermal resistance (Mk/W)
C_c	Capital cost ($)
u'_s	Cycle time parameter
r	Discount rate (%)
E_s	Electricity demand to be met by solar PV panels (kWh/year)
$E_{s\ \mathrm{available}}$	Electricity generated by each solar PV panels (kWh/year)
ρc	Heat capacity (MJ/m^3K)
t_c	Length o the heating season (days)
N_s	Number of solar PV panels
t'_c	Operating time ratio
C_p	Periodic cost ($)
$\bar{Q}_{BHE}$	Shallow geothermal potential (MWh/year)
t_s	Simulated lifetime (years)
u'_c	Simulation time parameter
λ	Thermal conductivity (W/Mk)
$E_{g\ \mathrm{available}}$	Thermal energy available per meter drilled (MWh/year-m)

T_{lim}	Threshold fluid temperature (°C)
n	Time point (Year 0, 1, 2, …)
L_{drill}	Total BHE drilling length
C_{t}	Total cost ($)
E_{g}	Total ground load (kWh/year)
T_0	Undisturbed ground temperature (°C)

Acronyms

ABS	Absorption ground-source heat pump
BHE	Borehole heat exchanger
CAD	Canadian dollars
CO_2	Carbon dioxide
COMP	Compression heat pump
COP	Coefficient of performance
DHW	Domestic hot water
EWT	Entering water temperature
GHG	Greenhouse gas
GIS	Geographic Information System
GGHP	Ground-coupled heat pump
GUE	Gas utilization efficiency
HDD_{18}	Heating degree days below 18°C
LCC	Life-cycle cost
LCCA	Life-cycle cost analysis
LCOE	Levelized cost of electricity
NPC	Net Present Cost
EERE	Office of Energy Efficiency and Renewable Energy
PV	Photovoltaic
RBOB	Reformulated gasoline blendstock for oxygen blending
RSI	R-value Systeme International
SH	Space heating
SHGC	Solar Heat Gain Coefficient
USD	United States dollars

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