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Geothermal Energy for Sustainable Food Production in Canada's Remote Northern Communities

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Abstract: The cold, remote, northern regions of Canada constitute a challenging environment for the provision of reliable energy and food supply to communities. A transition from fossil fuels to renewables-based sources of energy is one positive step in reducing the greenhouse gases from the energy supply system, which currently requires long-distance transport of diesel for electricity and heating needs. Geothermal energy can not only displace diesel for part of this energy need, it can provide a base-load source of local energy to support food production and mitigate adverse impacts of food insecurity on communities. In this proof-of-concept study, we highlight some potential benefits of using geothermal energy to serve Canada's northern communities. Specifically, we focus on food security and evaluate the technical and economic feasibility of producing vegetables in a "controlled environment", using ground sources of heat for energy requirements at three remote locations—Resolute Bay, Nunavut, as well as Moosonee and Pagwa in Ontario. The system is designed for geothermal district heating combined with efficient use of nutrients, water, and heat to yield a diverse crop of vegetables at an average cost up to 50% lower than the current cost of these vegetables delivered to Resolute Bay. The estimates of thermal energy requirements vary by location (e.g., they are in the range of 41 to 44 kW of thermal energy for a single greenhouse in Resolute Bay). To attain adequate system size to support the operation of such greenhouses, it is expected that up to 15% of the annually recommended servings of vegetables can be provided. Our comparative analysis of geothermal system capital costs shows significantly lower capital costs in Southern Ontario compared to Northern Canada—lower by one-third. Notwithstanding high capital costs, our study demonstrates the technical and economic feasibility of producing vegetables cost-effectively in the cold northern climate. This suggests that geothermal energy systems can supply the heat needed for greenhouse applications in remote northern regions, supplying a reliable and robust source of cost-competitive sustainable energy over the long-term and providing a basis for improved food security and economic empowerment of communities.

Keywords: Renewable and sustainable energy; Geothermal; Greenhouse; Food security; Cold and remote regions; Climate change; Economic development

1. Introduction

The world faces a number of new challenges from factors such as global population growth, economic and industrial development, urbanization, and lifestyle changes [1–6]. These include energy

and food insecurity, water scarcity, ocean pollution, and environmental threats, such as climate change, ozone layer depletion, acid rain, greenhouse gas (GHG) emissions, and air pollution [3,6–14]. Limitations of nonrenewable energy sources such as oil, coal, natural gas, and uranium [2,15,16], including the high cost of exploration, exploitation, and transportation, as well as ancillary factors such as political issues [17], have resulted in concerns over energy. Additionally, burning fossil fuels for electricity generation, heating and cooling needs is deemed a major contributor to emissions of GHGs [3,18–23].

Carbon dioxide (CO_2) is a principal GHG agent, and new, long-residence CO_2 is being added to the atmosphere through fossil fuel use. The burning of fossil fuels has produced nearly 500 billion tons of CO_2 since the early 18th century, with almost half of it remaining in the atmosphere [6,24,25]. Yearly anthropogenic CO_2 emissions have increased twofold in the last four decades [22,26,27]; CO_2 emissions in 2011 were 32 billion tons [26,27], and this is expected to reach 36 billion tons by 2020 [27–29]. Boden and Andres [28], as well as Heard et al. [30], reported that the atmospheric CO_2 concentration in 1995 was ~360 ppm, increasing to ~400 ppm in 2015.

To avoid the worst consequences of climate change and mitigate the threat of extreme warming (beyond a 2 °C increase in temperature), a transition to an energy system largely based on non-carbon renewable sources of energy, namely, wind, solar, bioenergy, hydro, and geothermal, is necessary. Geothermal energy exploitation comprises extraction and storage of thermal energy in the earth for different purposes such as power, district heating, and cooling [22]. Some versions of geothermal energy may help limit dependence on fossil fuels and provide a stable and long-lived energy source. Facility heating and cooling is a possible area where geothermal systems can contribute worldwide to GHG reductions and sustainability. Geothermal energy is also not significantly affected by geopolitics [31,32] or demand, as it is theoretically possible to obtain some degree of geothermal energy anywhere on the globe [33].

There are no commercial geothermal power plants in Canada, notwithstanding some parts of the country (e.g., British Columbia, Alberta, and Saskatchewan) having an appropriate potential for geothermal energy [34] from hot fluids. Several geothermal projects have been conducted in Canada [34]:

- A small-scale geothermal power plant (20 kW) at Meager Mountain in British Columbia; This project was not linked to the grid and has since been left in a predevelopment stage.
- An abandoned deep geothermal project (~2.5 km) based on fluids in sediments on the University of Regina campus for direct heating (both space and water) applications.
- A geothermal project in Springhill, Nova Scotia, based on heat recovery from flooded underground mines.

In this study, we provide a technical and economic assessment of the feasibility of using geothermal energy as a base for supporting economic production of food in isolated, cold regions of Canada. In a controlled "greenhouse" environment, favorable growing conditions can be created with sensors and devices for optimal lighting, nutrient, and water use, to provide conditions for an all-season operation to grow local fresh produce. With no GHG emissions, geothermal energy can provide the heating, cooling, and electricity needs of a facility, depending on location and the quality of the geothermal resource. A controlled environment greenhouse is energy intensive, with over 50% of operational costs dedicated to energy demands, the majority of which is to control temperature [35–39].

Geothermal heating of greenhouses is being used in a variety of countries including Australia, Iran, Tunisia, Japan and across Europe (particularly the Netherlands), showing that it is feasible in hot and temperate climates [37,40–43]. The Netherlands, as an example, is a worldwide leader in the export of agricultural products and knowledge [44], as it is the second largest agricultural exporter in the world after the USA [45]. The Netherlands, located in northeastern Europe on the edges of the North Sea, with a land area 270 times smaller than the USA, is a small and densely populated country that must use land efficiently [46]. Dutch farmers produce substantially more agricultural crops using

advanced greenhouses in comparison with outdoor environments. Many greenhouses are heated using geothermal energy through aquifers, ground source heat pumps (GSHPs), and deep geothermal sources [47,48], allowing farmers to control the greenhouses' temperatures without requiring any external energy inputs. It is predicted that approximately 20,000 geothermal systems (such as aquifer thermal energy storage) will be operational in the Netherlands by 2020 [49].

To fill the knowledge gap associated with the use of geothermal energy in cold climates, in this study we attempt to establish the technical and economic case for the use of geothermal energy as a local sustainable energy resource to support food production in northern Canada. The facility design is based on advanced "greenhouse operations" capable of high crop yields (>20 times those of conventional agriculture with < 95% water use and smart management of nutrient cycles). Ground Source Heat Pumps use the earth as a heat sink, heating or cooling surface air to control the temperature of a space [50–53]. While heating, GSHPs use a warm fluid (generally air, antifreeze fluid, or water) to exchange heat with the air in the space, and the cooled geothermal fluid is either reinjected or recirculated at depth; this mechanism is reversed when cooling an area with low-temperature water used to extract heat from the air and depositing it elsewhere [51,54,55]. Although GSHPs have high initial costs, particularly as retrofits, they offer low operating and maintenance costs, a coefficient of performance (COP) above 2, good lifespan, and are little affected by market prices of fuels or geopolitical perturbations [37,40,42]. Combined with the solar recharge of the heat repository, COP values as high as 8 are claimed (https://www.gshp.org.uk/Ground_Source_Heat_Pump.html) for GSHPs. The GSHP repository volume and depth are usually modest (<15 m), but large, deep repositories could allow large-scale seasonal storage of heat in cold climates.

Our study is also a proof-of-concept pilot for a cold climate geothermal energy initiative conducted to demonstrate that the local resource is sufficient to provide efficient temperature control and stable growing conditions with minimal environmental impact, while mitigating fresh vegetable shortages or high costs in isolated communities. The sites studied are Resolute Bay in Nunavut (NU), as well as Moosonee and Pagwa in Ontario (ON), complemented by additional assessments for several small Ontario communities. Currently, there is no geothermal food production in these communities, and there is limited literature regarding the use of geothermal energy as a means for supplying heat for greenhouses in cold, remote regions. This study addresses factors such as the optimization of vegetable variety, modeling of greenhouse energy demands, implementation of geothermal heating with a projected cost analysis, and comparing geothermal systems with other energy systems such as diesel generators and gas power plants.

2. Study Locale

Nunavut (NU) is remote, lightly inhabited, and poorly serviced; serious fresh food shortages are common, with 70% of Inuit preschoolers suffering from food insecure homes [56,57]. Resolute Bay (shortened to Resolute, Figure 1), with a modest population of 198, has had some degree of geothermal exploration and is one of the coldest inhabited places in the world with the highest monthly average temperature of +4 °C in July and lowest of −33 °C in February [58–60]. Moreover, it has an extreme solar cycle: 24-hour sunlight in the summer and no sun from early November to late February.

Energy in Resolute is produced through the burning of fossil fuels, leading to fuel insecurity (delivery, stockpiles, accidents, fires, etc.) in an area where heat is essential. The transportation costs of goods to Resolute are much higher than in the South: sea transport, the cheapest option, exceeds $400/ton, or $6100 Canadian Dollars (CAD) per 6 m container. NU has some of the highest grocery bills in Canada: average yearly grocery cost in 2007 was $19,000, compared to the national average of $7308 [56,61]. The high cost of essential supplies is further exacerbated by lower incomes in communities in these regions, with a median Inuit family income of $24,502, compared to the national median of $70,336 [62,63]. True power cost in NU is also significantly higher, with electricity costs ranging from 94.42 to 100.97 cents/kWh compared to the 2013 national average of 13.5 cents/kWh,

all facts that emphasize the need for sustainable and affordable food options [64,65]. Note that electricity and fuel are subject to various subsidies in the north to overcome some of the cost barriers.

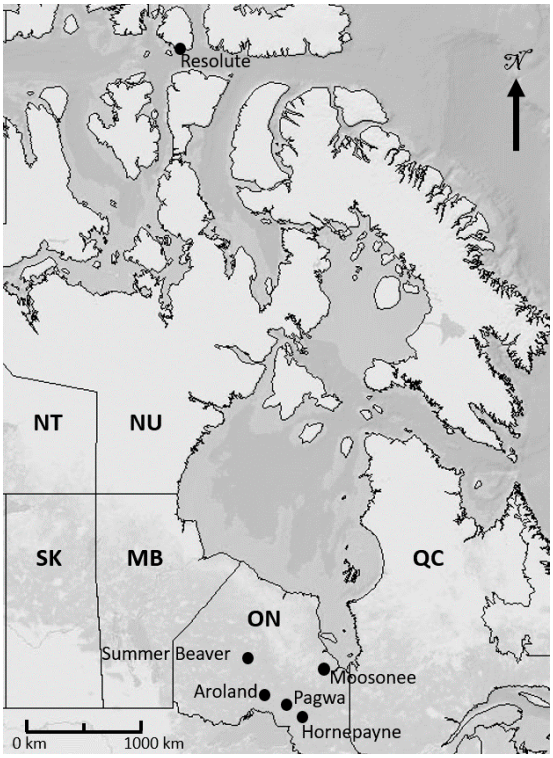


Figure 1. Map showing Resolute in Nunavut (NU) and regions of interest in Ontario (ON).

Of the indigenous people living in Ontario, approximately 50% are food insecure, as their communities are often in regions with poor agriculture potential [66] and distant from low-cost energy resources. Moosonee and Pagwa are indigenous communities (Figure 1) with populations of ~1500 and ~2900 in 2016, respectively. They are isolated from the rest of Canada, and agriculture potential is impaired by short, cool growing seasons and poor soil conditions [56,67]. Over 80% and 50% of people living in Moosonee and Pagwa are of indigenous identity, respectively, and the household income in these communities is low. As Moosonee and Pagwa are remote, the cost of groceries is higher compared with the communities in southern Canada, as demonstrated by food affordability studies [67]. Lower average incomes compounded with increased grocery costs are two of the most significant factors contributing to food insecurity.

Overall, more than a quarter of indigenous people in Canada have some level of food insecurity, compared to ~10% for all Canadians [68]. Wealth disparity and scarce local resources lead to dependency on packaged, high saturated fat food, and a low-fiber diet, with a lack of fruits and vegetables containing nutrition factors such as vitamin A, calcium, vitamin C, and folate [69]. Fresh vegetables at reasonable prices would help mitigate these issues and improve the quality of life for many of these remote communities.

3. Methodology

3.1. Building and Vegetable Optimization

When constructing and maintaining greenhouses in northern climates, emphasis is placed on heat conservation to limit energy demand; further, the produce chosen in various seasons should produce the maximum number of servings, with some variety. Space is thus at a premium, as it reduces greenhouse surface area per unit of product, and adequately lit vertical grow trays are a possible solution. Crops

should be optimized seasonally so that greenhouse temperatures can be as low as possible, as heat costs are driven by the difference between ambient and greenhouse temperatures. Most heat loss is through the greenhouse cover; it must allow solar energy in but also retain heat reasonably well. Walls and floors must be well insulated, and walls kept as short as feasible, so the greenhouse has a low cover-to-surface area ratio ($CA/SA = P_{value}$). Additionally, these structures must permit reasonable airflow and employee traffic while allowing light conveyance (wagons, wheelbarrows, etc.). Table 1 compares the P_{value} for structures with 129.6 m^2 of floor space. Remember that during the far northern summer (Resolute), the sun can fall on the greenhouse for approximately eight months, but for four of those months, it falls on the greenhouse from all directions during the day. Because this is a function of latitude, it leads to potentially different designs in different locations. Although hydroponic greenhouses are possible, conventional soil boxes that are adequately fertilized, exposed to grow lights, and watered were considered.

Table 1. P_{value} of several simple greenhouse shapes.

Shape	P_{value}
Pentagonal Prism	1.56
Geodesic Dome	2
Triangular Prism	0.66
Square-based Pyramid	2.3
Rectangular Prism	2.86

Geodesic domes, square-based pyramids, and rectangular prisms all have $P_{value} > 2$, so they were taken out of consideration. Although a triangular prism would have a remarkable P_{value} of 0.66, it restricts plant height and layout flexibility, with substantial heat loss to the peak. A standard pentagonal prism seems to provide a good P_{value} and allows for efficient internal layout. This shape provides the height for taller plants such as tomatoes, as well as the angled roof encouraging snow shedding in the winter months.

For the demonstration design, a 96′ × 30′ (1 ft is equal to 0.3048 m.) galvanized steel frame, which is to be built on a 2″ × 10″ (1 in is equal to 0.0254 m.) and 2″ × 6″ lumber frame, is chosen. The 2″ × 6″ floor joists spacing is 8″, whereas the crossing load-bearing members and exterior framing are made of 2″ × 10″ lumber to support the heavy weight of the plants and soil. Using AutoCAD™ (CA, USA) [70], several grow box designs and layouts were created to optimize the growing area; the final design (Figure 2) has 1443 ft^2 of 'primary' growing room when including a 48′ × 5′ hanging box the length of the greenhouse along the peak. The greenhouse cover is two layers of 5 mm Solexx™ polyethylene to maximize the heat retention of the building. A vestibule limits air exchange as people enter and exit, and at the opposite end, a room shelters the geothermal heat exchanger, water pump, and water tank.

Heat loss through the floor can be significant in permafrost climates; as a counteractive measure, 1.5″ expanded polystyrene (EPS) foam is laid over $\frac{1}{2}$″ oriented strand board (OSB), covered with 1″ R-3 insulated subfloor, then overlain with industrial grade linoleum for a water-repellent, easy-cleaning surface. Adding a second polyethylene layer, while preserving heat, limits the amount of sunlight penetrating and reaching the plants; therefore, RAY66 LED (Light-emitting diode) grow lights were chosen to provide plants with the necessary wavelengths of light, while offering maximum luminary efficiency. Other options are possible, such as a removable winter insulating cover on the exposed parts of the greenhouse, although these are not considered in this study. Small fans at the greenhouse peak are necessary to facilitate airflow and strategic placement of air ducts to distribute heat from the GSHP in a desired pattern are needed (different plants may have somewhat different temperature needs).

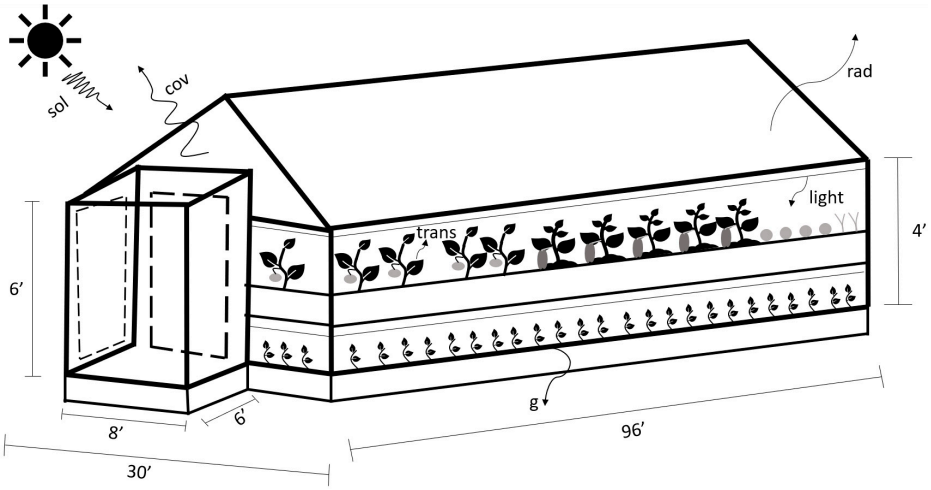


Figure 2. A schematic of the designed greenhouse.

Eight common greenhouse vegetables were chosen for analysis, including tomato, cucumber, sweet pepper, spinach, cabbage, broccoli, onion, and carrots. The maximum plant density of each was multiplied by their average yield per surface area (Table 2), and a minimum of three types of vegetables chosen to ensure variety and proper nutrient intake. As an example, a combination of 25% tomatoes, 30% sweet peppers, 25% cabbage, and 20% onions can provide a balanced vegetable intake (Table 3).

Table 2. Area needed per plant and yield per m^2 [71].

Plant	Area (m^2) Per Plant	Yield Per m^2	Yield Per Plant
Tomato	0.58	33.78	19.59
Cucumber	0.1089	21.02	2.89
Pepper	0.09	20.27	1.82
Spinach	0.04	50	2.0
Cabbage	0.16	71.43	11.4288
Broccoli	0.2025	8.38	1.70
Onion	0.0317	20.27	0.64
Carrots	0.016	38.46	0.62

Table 3. Optimal plant quantities and varieties.

Plant	# of Plants	% of Total Plants	Servings
Tomato	250	25	4898
Cucumber	0	0	0
Pepper	300	30	547
Spinach	0	0	0
Cabbage	250	25	2857
Broccoli	0	0	0
Onion	200	20	129
Carrots	0	0	0
Total	**1000**	**100**	**8431**

Given the vegetables chosen, an appropriate greenhouse temperature must be selected for the simulations. The optimal temperature for vegetables is between 18 and 28 °C; in cold locations a temperature closer to the lower bound, 20 °C, is appropriate [38,39,72], although this may inhibit the choice of tomatoes as a vegetable in favor of some others that prosper best in cooler conditions (kale, chard, etc.). The lower temperature choice provides adequate growing conditions while reducing temperature differential. If a heat-loving plant, such as tomatoes, gives good economic value, the

geothermal air ducting system can be used to keep a corner of the greenhouse several degrees warmer. Similarly, other crops can be placed in the best conditions with good design, but it is assumed that the average temperature is 20 °C in the structure.

3.2. Heating Demand Calculations

The heat input demand was calculated using conservation of energy, as follows,

$$Q_{tot} = Q_{\text{cov}} + Q_g + Q_{rad} - (Q_{trans} + Q_{sol} + Q_{light}) \quad (1)$$

where Q_{tot} is the total thermal energy needed, Q_{cov} is the heat loss through the cover, Q_g is the heat loss through the ground, Q_{rad} is the heat loss through radiation, Q_{sol} is the solar radiation input, Q_{light} is the heat input from the lighting, and Q_{trans} is the heat input from transpiration. Note that as this is a first-order feasibility study, and focus is placed on the most significant energy fluxes, so it does not account for sources or sinks other than the ones identified in Equation (1).

Heat loss through the cover is calculated by [73]

$$Q_{\text{cov}} = CA\left(\frac{T_{gh} - T_{amb}}{R_{solexx}}\right) \quad (2)$$

where R_{solexx} is the thermal resistance value for the cover of the Solexx™ material (2.1 Km^2/W [74]), which is doubled as there will be two layers (i.e., 4.2 Km^2/W); CA is the total cover area; T_{gh} is the greenhouse temperature (K); and T_{amb} is the ambient temperature (K) (Figure 3). Note that a double cover thickness has considerably more insulation value than a single cover thickness, but a conservative approach is adopted, assuming heat loss rates only halve with double thickness.

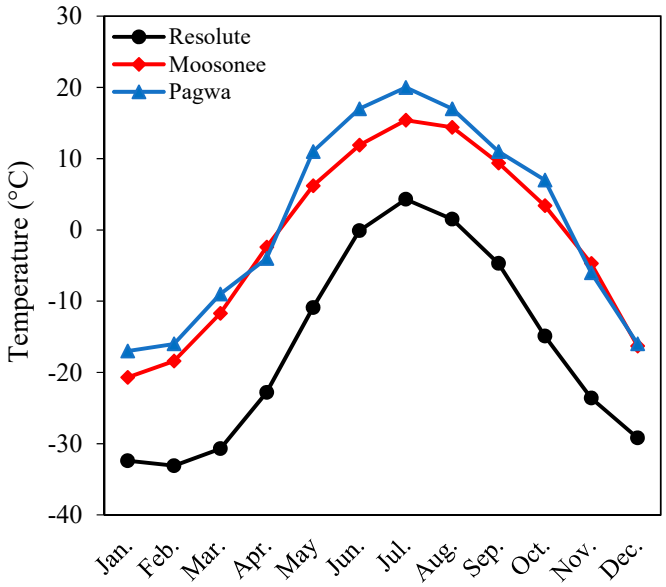


Figure 3. Average temperature for Resolute, Moosonee, and Pagwa [60].

Heat loss through the ground can be calculated by [73]

$$Q_g = SA\left(\frac{T_{gh} - T_g}{R_{value}}\right) \quad (3)$$

where T_g is the ground temperature, R_{value} is the thermal resistance value for the floor, and SA is the surface area of the greenhouse. In Equation (3), the greenhouse temperature was assumed to be a constant 20 °C, and the ground temperature was assumed to be a constant 0 °C. The value

of 0 °C is chosen because although most construction will be on solid ground (gravel, scree and indurated sediments), some cases may be constructed on soft sediments with ice-rich permafrost, and the temperature of the subgrade will have to be kept at or below 0 °C for stability.

Solar radiation enters the greenhouse in the form of short-wave radiation, but energy is lost by long-wave radiation. To account for this thermal loss through radiation, the following formula is used,

$$Q_{rad} = CA \,.\, \sigma \,.\, \varepsilon_{sol} \,(T_{gh}^4 - T_{amb}^4) \tag{4}$$

where σ is the Stefan–Boltzmann constant (5.67×10^{-8} W/m^{2}K^4) and ε_{sol} is the emissivity for polyethylene, considered to be equal to 0.2 [35].

Plant transpiration releases heat, which can be calculated by [75–77]:

$$Q_{trans} = 34.9\, PA \tag{5}$$

where PA is the plant area. In Equation (5), 34.9 (W/m^2) is obtained with the average transpiration for the following conditions [75,77]: T_{gh} = 20 °C, ($T_l - T_{gh}$) = 5 °C, and relative humidity (RH) equals 75%, where T_l is the leaf temperature. The parameter of PA is given by

$$PA = \sum LAI \,.\, TA \,.\, n_{pla} \tag{6}$$

Here, LAI is the leaf area index, TA is the soil area per plant, and n_{pla} is the number of plants. Table 4 shows the amounts of LAI and TA for the plants considered in this study.

Table 4. Leaf area index (*LAI*) and soil area per plant (*TA*) for different vegetables [71,78–80].

Plant	LAI (m^2/m^2)	TA (m^2)
Tomato	3	0.58
Cucumber	3.5	0.1089
Pepper	5	0.9
Spinach	0.9	0.04
Cabbage	1.15	0.16
Broccoli	0.97	0.2025
Onions	2	0.0317
Carrots	0.9	0.016

Thermal energy from solar radiation can be computed by [81]

$$Q_{sol} = I_r \,.\, \tau_{sol} \,.\, CA \tag{7}$$

where I_r is average solar insolation (kWh/m^2/month), τ_{sol} is the solar transmissivity (it is equal to 0.75 for polyethylene cover [35]). For Pagwa, ON, the solar insolation of Caramat, ON, 80 km southwest, is used (Table 5).

Table 5. Solar insolation (kWh/m^2/h) of Resolute, Moosonee, and Pagwa [82].

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Resolute	0	0.16	1.35	3.91	6.22	6.48	5.11	2.93	1.36	0.33	0.01	0
Moosonee	1.13	2.18	3.58	4.87	5.46	5.75	5.44	4.47	2.97	1.71	0.96	0.83
Pagwa (Caramat)	1.24	2.23	3.58	4.86	5.55	5.82	5.76	4.75	3.18	1.89	1.09	0.94

LED lights provide the full spectrum of light that plants need and are quite efficient for photosynthesis but produce heat. To estimate heat produced by LED lights, the following formula can be used [83],

$$Q_{light} = P_l \,(1 - \eta)\, n_{light} \tag{8}$$

where P_l is the wattage of each light unit (or power of lighting), η is the light efficiency, and n_{light} is the number of lights needed in the greenhouse. For this calculation, 120 W is used (wattage of RAY66 systems) and an efficiency of 15% is considered [84].

3.3. Geothermal Supply Estimation

Using recently published geothermal data [85], temperature at depth can be estimated in Resolute [86], and it is possible for estimates to be made elsewhere within the Canadian Shield (CS) region. A numerical simulation using Python® code (version 3.7) is implemented to compute the heat at depth in Resolute and the CS. The calculations for the CS are straightforward, but as Resolute is situated above 1000–1500 m (in this study, 1500 m is used) of permafrost, and the Arctic Sedimentary Basin (ASB), possesses a higher than average heat flow and geothermal gradient, it provides a unique scenario [58].

Heat extracted by the water (Q_w) at depth is calculated using Fourier's formula for convective heat transfer within a pipe, as follows [73],

$$Q_w = \frac{2\pi k_p \left(T_r - T_w\right)}{\ln\left(\frac{r_o}{r_i}\right)} \tag{9}$$

where r_o is the outer radius of the pipe, r_i is the inner radius of the pipe, T_R is the rock temperature (K), T_w is the water temperature out of the geothermal heat pump (K), and k_p is the pipe thermal conductivity. The quantities of parameters used in Equation (9) are k_p = 0.4 W/mK [87], T_w is 275 K [88], and r_o and r_i are equal to 0.0381 m and 0.0254 m, respectively.

The water temperature at depth is calculated by [89]

$$T = \left(\Delta T_{x-1} + \left(\frac{\Delta Q_{w,\,x-1}}{C_p\,\dot{V}}\right)\right) + \left(\frac{Q_w}{C_p\,\dot{V}}\right) \tag{10}$$

where $\dot{V}$ is the flow rate and C_p is the heat capacity of water. For this simulation, the flow rate is set at 0.945 kg/s and the heat capacity of water is 4200 J/kgK. Equation (10) is iterative, calculating the water temperature at every 50 m of depth. Pumps of several capacities along with their prices (Table 6) are analyzed to decide which system is the most cost-efficient [88].

Table 6. Capacity, cost and electrical power consumption of several geothermal pumps [88].

Capacity (kW)	Power input (kW)	Price (CAD)
17	5	5700
30.5	10	25,000
60	15	50,000
73	18	65,000
87	25	75,000
107	27	100,000
122	30	125,000

Borehole Length Estimation

A closed-loop pipe configuration was considered for this study, where the working fluid (e.g., water) is injected, heated at depth, and extracted from a single or an array of borehole(s). As these locations are unconventional, an adaptable approach must be taken; therefore, a single borehole with a U-pipe was chosen for these calculations. Using the simulation conducted (Equations (9) and (10)), it is found that the temperature loss during extraction is minimal in ON (< 2 °C); therefore, a 1100 m borehole would suffice to provide 6 °C water to the geothermal heat pumps (Table 7). The temperature and depth of the permafrost in Resolute are used in the Python® code, providing an estimate of 11 °C

change in water temperature from the heat reservoir to the pump, concluding that to provide the pump with 6 °C water, a depth of 2500 m needs to be reached (Table 8). Note that, as illustrated in Tables 7 and 8, the water never reaches thermal equilibrium with the rock.

Table 7. Ontario ground and water temperature at depth.

ON	700 m	800 m	900 m	1000 m	1100 m
Ground T (°C)	17.5	20.0	22.5	25.0	27.5
Water T (°C)	5.8	6.5	7.1	7.9	8.5

Table 8. Resolute ground and water temperature at depth.

Resolute	1900 m	2100 m	2300 m	2500 m
Ground T (°C)	25.5	59.5	66.5	73.5
Water T (°C)	13.6	15.5	17.4	19.2

4. Results and Discussion

Various assumptions are needed to translate a first-order analysis into a feasibility assessment for geothermal greenhouses in some of the most remote locations in the world. Regarding vegetable growth, it is assumed that plants would be arranged in a maximum density configuration, that there is no loss of crop, transpiration is at a maximum, and the plants produce the average amount of servings. The thermal conductivity of the cover is assumed linear with thickness, and the solar transmissivity and emissivity do not change. The temperature within the greenhouse is a constant 20 °C, and the ambient temperature and solar insolation are average and constant values. When identifying the geothermal potential, it is assumed that the heat extraction would be linear and the pipe is in thermal equilibrium with the rock. Furthermore, reservoir heat loss over time with extraction is not accounted for. In further research, it will be necessary to perform calibrations and experiments and use more complex thermal modeling.

4.1. Comparison between Localities

Resolute is located on the Arctic Basin, with a geothermal gradient of 0.035 °C/m compared to a geothermal gradient of 0.025 °C/m in ON [86]. The depth needed to provide warm water is significantly deeper in Resolute (2500 m) compared to ON (1100 m). The energy demand for all localities was calculated using Equations (1)–(8). The energy demand of Resolute is higher every month than in ON (Figure 4), with the energy demand ranging from 41 to 44 kW and 40 to 43 kW, respectively. Although the energy demand in ON is less, it is not drastically different, implying that the insulation is effective at retaining heat and, conversely, that the energy demand of greenhouses in northern regions is significant.

A summary of the servings provided by greenhouses and the percentage of those satisfied by a potential greenhouse are given in Tables 9 and 10. The potential servings are calculated by multiplying the population by 8 (the suggested number of vegetable servings per person a day [90]), and further multiplying by 365 to represent a year. The servings generated from the greenhouses are calculated using the number of servings as discussed in Section 3.1, assuming 4 months per cycle of production, which allows for three growing cycles in a year. Multiple small communities in ON are included for this comparison, as their energy demand and geothermal potential would be comparable to Moosonee and Pagwa (Figure 1). The number of servings produced by the greenhouse can be optimized by staggered grow cycles and using the area below the grow boxes as seedlings area, which is accounted for in the cost analysis, ensuring constant production of vegetables.

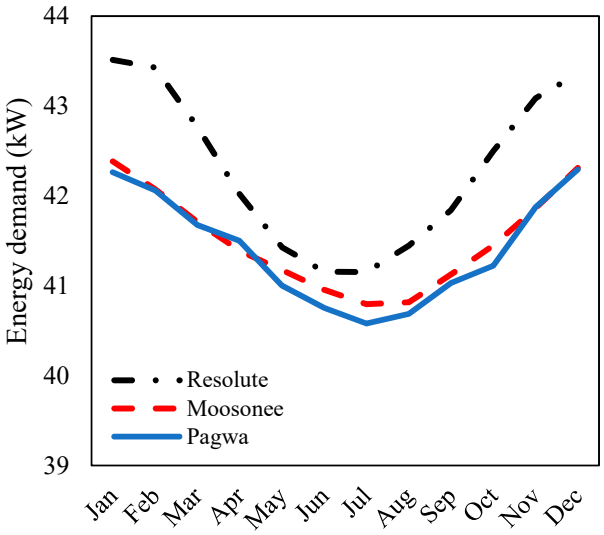


Figure 4. Energy demand for a single 96′ × 30′ greenhouse.

Table 9. Vegetable servings per number of greenhouses.

Code	Greenhouse	Servings
A	1 × 48′ × 30′	12,384
B	3 × 48′ × 30′	37,152
C	1 × 96′ × 30′	25,293
D	3 × 96′ × 30′	75,879

Table 10. Yearly servings of vegetables satisfied per greenhouse scenario.

	Resolute	Moosonee	Pagwa	Summer Beaver	Aroland	Hornepayne
Population (in 2016)	198	1481	2865	382	366	980
Yearly servings	578,160	4,380,000	8,365,800	1,115,440	1,068,720	2,861,600
% Satisfied (A)	2.1	0.3	0.15	1.1	1.2	0.4
% Satisfied (B)	6.4	0.8	0.4	3.3	3.5	1.3
% Satisfied (C)	4.4	0.6	0.3	2.3	2.4	0.9
% Satisfied (D)	13.1	1.5	0.9	6.8	7.1	2.7

4.2. Additional Infrastructure

To supply plants with water, a drip system should be installed to maximize efficiency. In an enclosed greenhouse with close spacing and drip irrigation, each plant would need a maximum of 0.74 L/day of water, so the greenhouse would need a maximum of 740 L/day of water [91,92]. To supply this, a pump is needed; the Leader Ecojet™ pump (Bientina, Italy) can provide 3634 L/hr using 1.4 kW of energy [93], and the water would be stored within a 2581.65 liter tank [94] within the back room beside the geothermal pump.

To supply the energy needed to each greenhouse, an industrial diesel generator must be installed. Large industrial generators can generally operate for 8 to 12 hrs, although larger fuel tanks can be installed. A 100 kW Perkins diesel generator would be needed for three greenhouses for powering the lights, geothermal pump and water pump [95]. Additionally, ducting would be needed to transport warm air to the greenhouses; a 4″ cylindrical pipe with four heat registers running along each side would suffice to heat each greenhouse. Note that geothermal energy systems (GESs) can supply the heat needed for warm water consumption (at desired temperatures) to water the plants in the greenhouses of cold regions as well. For this purpose, a heat exchanger can be added in the system for exchanging heat between freshwater (low temperature) and extracted water (high temperature) from the extraction well of the GESs.

4.3. Economic Considerations

4.3.1. Capital Costs

For greenhouses to be feasible, not only do they need to grow vegetables and extend growing seasons, but they must be economical. To calculate the cost of building these greenhouses, the quantity of supplies and subsequent cost of materials are calculated (Tables 11 and 12). For example, the cost of building materials, the lumber, insulation, and flooring are gathered from commercial sources; the cost of LED lighting, steel frame, and the cover are collected from their corresponding websites [96–98]. In the case of building a greenhouse in Resolute, the transportation of materials by Sealift [99] is needed; the prices of which can be found on their website. In ON, the cost of shipping was not calculated, as it is difficult to find appropriate rate listings. This cost analysis should be taken as a minimum, because the cost of soil, grow boxes, and vegetable seeds was not considered.

Table 11. Summary of generator costs [95].

Power (kW)	Cost (CAD)
35	17,000
45	18,000
100	19,750
150	23,300
300	51,500

The most expensive endeavor is drilling, particularly in Resolute, estimated to cost 4.8 million CAD in Resolute, whereas boreholes would likely cost 1.4 million CAD in Ontario (solid lines in Figure 5). This estimate accounts for the average cost of workers, mud, bits and the rig, although it does not account for the cost increase associated with drilling through permafrost and transporting the equipment [100].

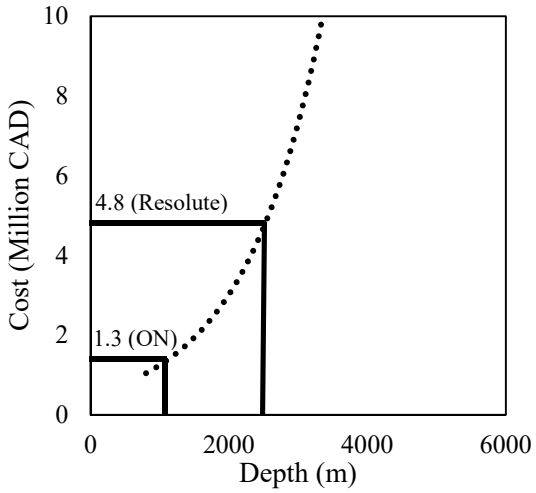


Figure 5. Drilling cost vs. depth, modified from Heidinger [100].

Table 12. Cost for 96′ × 30′ greenhouses in (**a**) Resolute and (**b**) ON in CAD.

Item	1 Greenhouse	3 Greenhouses
96′ × 30′ frame	$5300	$15,900
20′ sealift containers	$12,400	$37,200
Solexx^{TM} double layering	$27,200	$81,600
RAY66 LED grow lights	$48,880	$146,640
Subfloor	$6322	$18,966
1/2′′ OSB	$1620	$4860
1.5′′ EPS	2070.0	$6210
Linoleum tile	$2736	$8208
2′′× 10′′× 12′	$504	$1512
2′′× 6′′× 12′	$2250	$6750
3 Doors	$750	$2250
Water pump	$345	$1035
Irrigation hose	$115	$345
Heating ducts	$530	$1590
Water tank	$682	$2046
Building costs	$111,704	$335,112
Max. Energy consumption (kW)	43.5	88.7
	Geothermal Heated	
Boreholes	$4,800,000	$14,400,000
Pumps	$50,000	$100,000
	1 × 60 kW	1 × 107 kW
Generator	$18,000	$23,300
Total cost	**$4,979,704**	**$14,854,862**
Energy input needed	**35.6**	**91.8**
SPF *	**2.8**	**3.2**

(**a**)

* Seasonal performance factor.

Item	1 Greenhouse	3 Greenhouses
96′ × 30′ frame	$5300	$15,900
Solexx^{TM} double layering	$27,200	$81,600
RAY66 LED grow lights	$48,880	$146,640
Subflooring	$6322	$18,966
1/2′′ OSB	$1620	$4860
1.5′′ EPS	$2070	$6210
Linoleum tile	$2736	$8208
2′′× 10′′× 12′	$504	$1512
2′′× 6′′× 12′	$2250	$6750
3 Doors	$750	$2250
Water pump	$345	$1035
Irrigation hose	$115	$345
Heating Ducts	$530	$1590
Water tank	$682	$2046
Building costs	$99,304	$297,912
Servings	24,765	74,295
Max. Energy consumption (kW)	42.5	86.7
	Geothermal Heated	
Boreholes	$1,300,000	$5,200,000
Pumps	$50,000	$100,000
	1 × 60 kW	1*107 kW
Generator	$18,000	$23,300
Total cost	**$1,467,304**	**$5,617,662**
Energy input needed	**35.6**	**91.8**
SPF	**2.9**	**3.3**

(**b**)

4.3.2. Operational Costs

While the greenhouse is in operation, the generator must be supplied with 180 liters of diesel every day per greenhouse and 552 liters of diesel every day for three greenhouses. Although this is a substantial amount of fuel, it would be significantly cheaper in Resolute and ON to run a dedicated and appropriately sized diesel generator instead of using local power generation (Figure 6). After eight days of operation in Resolute, the initial cost of the generator and operational cost of diesel is surpassed by the cost of using local power generation; in ON this occurs after 750 days. For these analyses, a cost of $1.15/L of diesel is used, a value deemed reasonable through experience in each area. For electricity, a lower value of $0.94/kWh in Resolute and a peak-hr cost of $0.32/kWh in ON is used [65,101]. Table 13 shows the operational costs for the considered greenhouses in Resolute and ON.

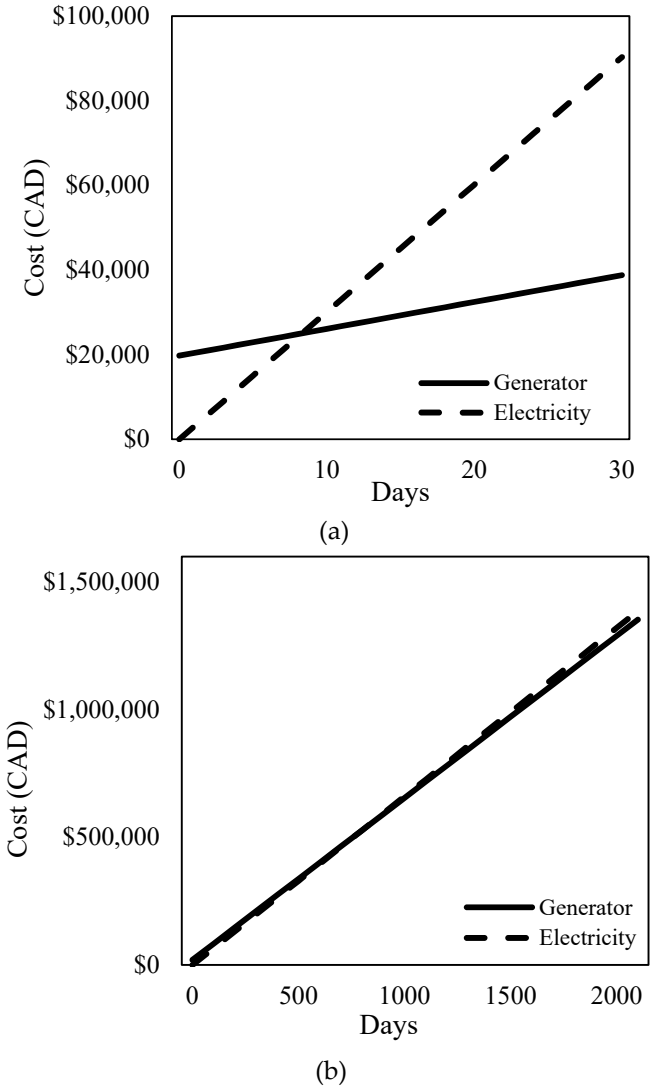


Figure 6. Cost of diesel generator vs. electrical power in (a) Resolute and (b) ON.

According to the economic analysis conducted in this study, as an example, the average prices for tomatoes and onions in NU are $9.04 and $5.01 per kilogram, respectively [102]. This corresponds to $6.11 per serving of tomato and $5.96 per serving of onion, using grams per serving from USFDA [103]. Comparing these values to the cost per serving determined in Table 13, growing vegetables in Resolute can reduce the cost up to half.

Table 13. Operational costs for 96′ × 30′ greenhouses.

	1 Greenhouse	3 Greenhouses	Location
Diesel for generator (L/hr)	7.5	23	
Water for vegetables (L/day)	7.4	177.5	
Diesel (daily)	207 CAD	635 CAD	
Electricity (daily)	820 CAD	3,010 CAD	
Yearly cost (diesel)	75,555 CAD	231,702 CAD	Resolute
Yearly cost (electricity)	299,300 CAD	897,900 CAD	
Cost per serving	3 CAD	3 CAD	
Diesel (daily)	207 CAD	635 CAD	
Electricity (daily)	238 CAD	660 CAD	
Yearly cost (diesel)	75,555 CAD	231,702 CAD	Ontario
Yearly cost (electricity)	86,870 CAD	260,610 CAD	
Cost per serving	3 CAD	3 CAD	

4.3.3. Comparison of Different Energy Production Systems

For comparison purposes, the results obtained from the studied geothermal systems (diesel and electricity just for powering the lights and pumps) are compared with two other energy production systems: diesel generator and gas power plant. Figure 7 compares different energy production systems in terms of the cost over 30 years for Resolute and the communities in ON. In the cost analysis, the authors have ignored various costs including oil transportation and fuel storage, transport pipeline construction, maintenance of the systems, and public health because of GHG emissions and other environmental pollution costs.

According to the Government of Nunavut [104], the price of diesel fuel for heating purposes is designated as $1.0658 per liter (all taxes included) for various communities from July 1, 2019. Of the true cost, the Government of Nunavut is currently subsidizing ~75 percent to reduce energy prices and make it more affordable for consumers [105]. As illustrated in Figure 7a, the use of geothermal systems for the considered communities in ON is cost-effective compared to diesel generation. However, the use of a gas power plant is cheaper if the Government of Ontario can provide the natural gas for these communities; in this case, the capital cost of construction of transportation pipeline and its maintenance must be considered. In Resolute, the geothermal systems are cost-competitive compared to diesel generator over a period of 30 years (Figure 7b); gas power plants are not feasible in Nunavut due to a lack of infrastructure. Overall, geothermal systems in both Resolute and the considered communities in ON appear to be cost-effective and practical solutions. Mahbaz et al. [106], Kazemi et al. [24], Soltani et al. [22,23], and Dehghani-Sanij et al. [107] reported that geothermal energy is renewable, environmentally friendly, local, reliable, resilient, self-contained, self-powered, year-round, robust, and flexible in terms of energy provision. Therefore, the use of geothermal energy systems in cold and remote regions of Canada is an appropriate solution to provide heat for inhabitants.

Another notable point is that the lifetimes of diesel generators and gas power plants are 20–25 years [108] and 25 years on average [109], respectively, which are generally lower than geothermal power systems' lives. According to Gringarten and Sauty [110], Lippmann and Tsang [111], and Wellmann et al. [112], the reasonable operating period of geothermal energy systems is ~30 years, although it has been reported that in some cases, it is even greater [113]. For instance, the 3.2 MW Bjarnarflag geothermal power station was constructed in 1969 (50-year lifetime), located in the northeastern region of Iceland [113].

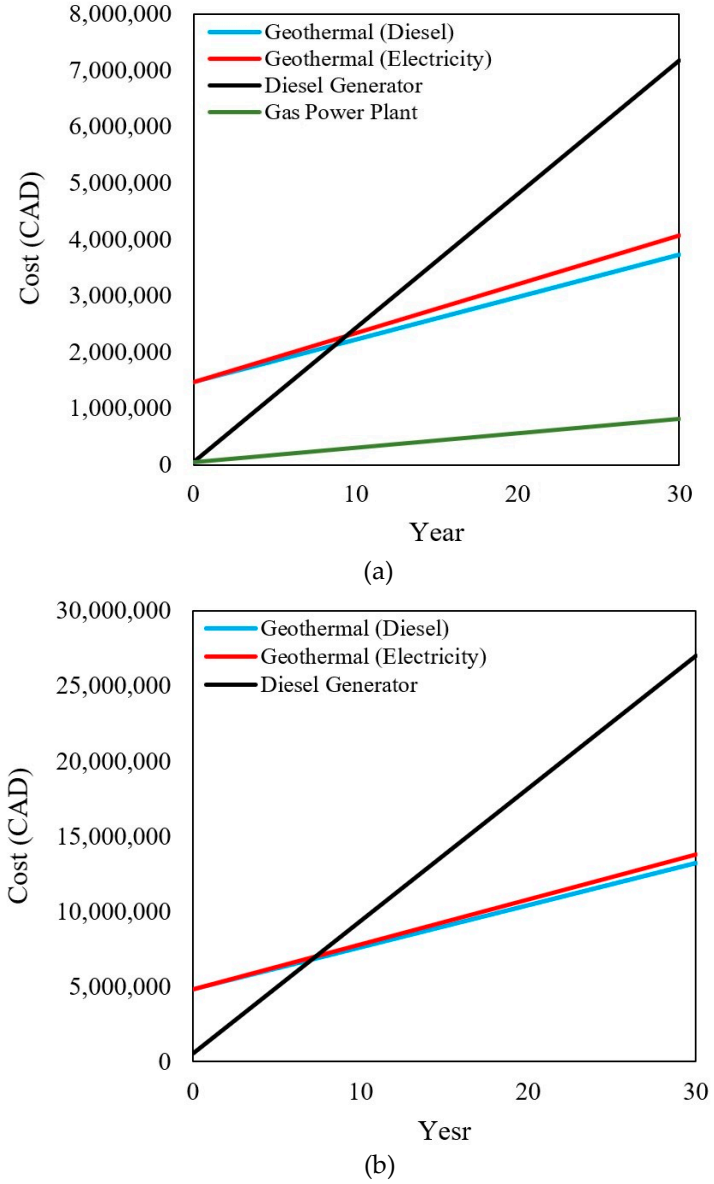


Figure 7. Comparison of different energy production systems in terms of cost for the considered communities in (**a**) ON and (**b**) Resolute.

The use of geothermal energy systems in cold climates such as Canada's northern regions has a number of advantages, including diminution of power energy consumption; reduction, and even elimination of, oil transportation and storage; job creation for local people; reduction in environmental and public health threats; and improvement of life standard in these areas [107]. The high initial investment cost is a key obstacle to development of geothermal power plants. To solve this issue in Canada's northern communities, the governments of Yukon, Northwest Territories, and Nunavut, along with the Federal government, can build and operate the geothermal power plants for these communities (even with the help and support of private investors), instead of paying a large amount of subsidies for energy supply (mainly for diesel fuel). According to Figure 7, geothermal energy is overall more cost-effective approximately 10 years after the beginning of operation.

4.4. SWOT Analysis

SWOT analysis is a useful tool to evaluate a system or project through identifying its strengths, weaknesses, opportunities, and threats that it faces during operation [114]. Strengths and weaknesses typically concentrate on the present situation, whereas opportunities and threats focus on the future [115]. The positive effects and the potential problems related to the implementation of geothermal greenhouses in cold and remote regions are addressed in the following.

- Strengths: Unlimited geothermal resources accessible (in principle, but may require more drill holes). Advances in technology development and availability (deep and shallow). Substantial economic benefits for end users. Help for indigenous communities in remote regions. Improving food security in remote regions. Increasing public health of indigenous communities. Minor environmental issues.
- Weaknesses: High initial investment costs. Inadequate geological studies and economic assessments.
- Opportunities: Increase government support. Reduced costs because of technological development and local food products. More financial support for using geothermal energy.
- Threats: Price of fossil fuels, especially in the use of diesel generators. Lack of executive promotion policy towards geothermal energy.

4.5. Climate Change

Climate change is a global issue that disproportionately affects northern climates, the populations of which often rely on snow and ice for winter transport and hunting or trapping [116]. Sea-ice stability and snow cover have decreased in the past century, making it harder to access hunting grounds, as the primary mode of transportation is by snowmobile and the historic migration routes of game animals are either altered or vanish altogether [116,117]. This, in turn, affects the availability of country food for indigenous people, making them more vulnerable to food insecurity and increasing their dependence on cheap, nutrient-poor foods, and the health risks associated with a poor diet.

4.6. Public Health

Indigenous communities have historically relied heavily on country/traditional foods (caribou, deer, seals, whales, fish, etc.) harvested by individuals, but as these communities transitioned from near-nomadic tribes to settlements, the proportion of individuals buying nontraditional foods has increased [118]. Unlike Greenland, Canada does not have marketplaces for traditional foods, forcing individuals to engage in hunts to provide their households with food; these hunts are quite resource intensive, needing snowmobiles, ATV's, boats, ammunition, etc. [118,119].

The lack of professional hunters compounds the lack of traditional food as there is a decrease in regular and intense hunters in Inuit and indigenous households as well as the additional stress added to select species deemed more favorable (e.g., caribou) [118–120]. The rate of heart disease and diabetes has increased in indigenous populations as their diets changed from country to nontraditional foods, because low-nutrient, high-energy foods (refined carbohydrates and cooking oils) are cheaper than perishable foods in these areas [121,122].

5. Conclusions

Geothermal energy is a safe, predictable, and environmentally sustainable resource with good potential for delivering energy services to communities in northern Canada. Geothermal energy can be controlled to meet demand, requires minimal maintenance, and it has a very low GHG emissions profile on a life cycle basis of assessment. At the global level, geothermal energy is a ubiquitous resource of non-carbon energy. The primary barrier to wide-spread exploitation of geothermal energy is the 'up-front' capital requirements, although it can be shown on the basis of levelized cost of energy that it can be a cost-effective option over a long return period. The ease of access to 'near-surface' sources

of geothermal energy often depends on geography; for example, geothermal energy is extensively utilized in Iceland (albeit an exceptional case).

In this proof-of-concept study, we have shown the viability of an innovative solution to reduce carbon emissions and, in particular, offer a solution to the production of food in cold, remote regions of Canada by the use of a sustainable source of local energy: geothermal energy. We have developed a baseline of information and insights to promote additional research and assessment to advance consideration of geothermal energy development in various locations. If there is a serious desire to mitigate the current food insecurity in northern Canada and improve health outcomes, the one practical and reasonable solution is to provide adequate and healthy food. Building geothermal greenhouses in these locations can improve food security and give a greater sense of community, a deeper relationship with fresh produce, and can also promote geothermal approaches as sustainable and stable sources of thermal energy for buildings. Although the design is not without fossil fuels, it shows that a hybrid approach to geothermal energy is suitable to justify the use of geothermal heat for commercial and community use. Undoubtedly, better designs will emerge.

In the design of a controlled "greenhouse operating system", to ensure maximum production, a staggered growing schedule and starting of seedlings below the grow boxes is encouraged. The building system would need a generator or connection to the electrical grid to operate the geothermal pump and lighting, but with a SPF of ~2.8 and ~3.2 for one and three greenhouses, respectively, a reasonable level of energy efficiency is achieved. Geothermal greenhouses seem to be an economically, environmentally and socially responsible approach to food provision. The greenhouses have significant costs; building three greenhouses in Resolute will cost ~15 million CAD to build, whereas ON has a lower capital expense of 5.7 million CAD; both locations would require diesel to operate a large generator with an operational cost of 230,000 CAD/year. Moreover, they will be resource intensive increasing the operational cost beyond the scope of this project as each greenhouse will require 740 L/day of water as well as the cost associated with soil, vegetable seeds and worker wages. Nonetheless, growing vegetables in Resolute can reduce the price of vegetables in the area up to half, reducing the cost from ~$6/serving to $3 per serving. In addition, based on the cost analysis, using geothermal systems for the communities in ON is cost-effective toward diesel generators, but not for gas power plants. In Resolute, geothermal systems are totally cost-competitive compared to diesel generators over a period of 30 years. The use of gas power plants is not possible in Resolute because of the absence of natural gas infrastructure and sources. Note that these calculations are for 30 years, and if it is considered that a life span is 20 years greater, then the geothermal systems will be more cost-effective with far less environmental impact.

This study shows that it is feasible for cold climate geothermal greenhouses to provide vegetables for remote communities. Future research should focus on using more complex modeling software, analogue models and the implementation of geothermal greenhouse pilot projects in northern climates. Such work would promote geothermal energy as well as encourage food sustainability in remote regions. It will trigger innovations and new methods to conserve and recycle energy, while providing important services to the community. Our study, focusing on production of vegetables in a harsh northern environment, is a powerful illustration of how several multiple goals of food security, positive health outcomes, economic development and economic empowerment of indigenous communities and sustainable energy use can be brought together to reinforce positive outcomes.

Nomenclature

CA	Cover area, m^2
C_p	Specific heat capacity, J/kgK
I_r	Solar insolation, $kWh/m^2/day$
k	Thermal conductivity, W/mK
LAI	Leaf area index, m^2/m^2
PA	Plant area, m^2
P_l	Power of lighting, W
P_{value}	Ratio of cover area to surface area, -
Q	Thermal energy rate, W
R	Thermal resistance, Km^2/W
r	Radius, m
RH	Relative humidity, %
SA	Surface area, m^2
TA	Soil area, m^2
T	Temperature, °C
$\dot{V}$	Volumetric flow rate, m^3/s
Greek symbols	
ε	Emissivity, -
η	Efficiency, -
σ	Stefan–Boltzmann constant, W/m^2K^4
τ	Transmissivity, -
Subscripts	
amb	ambient
cov	cover
g	ground
gh	greenhouse
i	inner
l	leaf
light	lighting
o	outer
p	pipe
pla	plants
R	rock
rad	radiation
sol	solar
tot	total
trans	transpiration
w	water

Abbreviations

ASB	Arctic Sedimentary Basin
CAD	Canadian Dollars
CS	Canadian Shield
EPS	Expanded Polystyrene
GESs	Geothermal Energy Systems
GHG	Greenhouse Gas
GHPs	Geothermal Heat Pumps
GSHPs	Ground Source Heat Pumps
ON	Ontario
OSB	Oriented Strand Board
NU	Nunavut
SPF	Seasonal Performance Factor

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