Development of a Building Energy Model in Kuujjuaq: Proposing Sustainable Energy Solutions

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RÉSUMÉ

Pour les communautés nordiques isolées qui dépendent principalement du diesel pour la production d'électricité et le chauffage des locaux, la transition énergétique est un défi majeur. Les systèmes de pompe à chaleur géothermique assistée par l'énergie solaire (SAGCHP) sont une alternative intéressante qui a été étudiée dans ce rapport pour alimenter le Forum de Kuujjuaq, un centre multi-activités situé au Nunavik, Canada. Un important manque de données sur les besoins énergétiques des bâtiments communautaires dans un contexte de climat subarctique est aujourd'hui constaté dans la littérature. Cette étude a permis de mieux documenter la consommation d'énergie d'une grande infrastructure, mais aussi la production électrique d'un système photovoltaïque récemment installé sur une partie du toit. Un modèle complet a été développé pour analyser la demande de chauffage du bâtiment et simuler les performances d'une pompe à chaleur géothermique couplée à des panneaux photovoltaïques. Les résultats des simulations indiquent une consommation annuelle de chauffage de 574 MWh, proche de la valeur réelle observée de 577 MWh, avec la ventilation représentant 375 MWh. Le système de pompe à chaleur géothermique nécessite environ 60 forages à des profondeurs comprises entre 160 et 200 mètres pour répondre à la demande. Des panneaux photovoltaïques supplémentaires couvrant la totalité du toit pourraient fournir en moyenne 30 % de la demande annuelle en énergie de la pompe à chaleur, avec des variations saisonnières allant de 22 % en hiver à 53 % au printemps. L'analyse économique et environnementale suggère des économies annuelles potentielles de 164 960 $ CA et une réduction annuelle des émissions de 79,8 tCO2eq, en incluant les bénéfices de l'exportation des surplus d'énergie solaire vers le réseau local. Cette étude fournit des informations précieuses sur la consommation d'énergie des bâtiments non résidentiels dans des conditions subarctiques et démontre la viabilité technique des systèmes SAGCHP pour des applications à grande échelle dans des communautés isolées.

ABSTRACT

Energy transition is a challenge for remote northern communities mainly relying on diesel for electricity generation and space heating. Solar-assisted ground-coupled heat pump (SAGCHP) systems represent an alternative that was investigated for the Kuujjuaq Forum multi-activity facility in Nunavik, Canada. The energy requirements of community buildings facing a subarctic climate are poorly known. This study provided an opportunity to better document the energy consumption of large infrastructure, es-pecially considering the recent solar photovoltaic system installed on part of the roof. A comprehensive model was developed to analyze the building's heating demand and simulate the performance of a ground-source heat pump (GSHP) coupled with photo-voltaic (PV) panels. Results indicate an annual heating consumption of 574 MWh, close to the real observed value of 577 MWh, with ventilation accounting for 375 MWh. The GSHP system requires around 60 boreholes at depths between 160 and 200 meters to meet the demand. Additional PV panels covering the entire roof could supply 30% of the heat pump's annual energy demand, with sea-sonal variations from 22% in winter to 53% in spring. Economic and environmental analysis suggest potential annual savings of 164,960 CA$ and 79.8 tCO2eq emissions reduction, including benefits from exporting solar energy surplus to the local grid. This study provides valuable insights on non-residential building energy consumption in subarctic conditions and demonstrates the technical viability of SAGCHP systems for large-scale applications in remote communities.

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LIST OF ABBREVIATIONS, ACRONYMS AND VARIABLES

Abbreviations and acronyms

BTES	Borehole Thermal Energy System
COP	Coefficient Of Performance
DHW	Domestic Hot Water
EFT	Entering Fluid Temperature
GCHP	Ground-Coupled Heat Pump
GHE	Ground Heat Exchanger
GHG	Greenhouse Gas
GSHP	Ground-source Heat Pump
NPC	Net Present Cost
OA	Outdoor Air
PV	Photovoltaic
SAGCHP	Solar-Assisted Ground-Coupled Heat Pump
SF	Scale Factor
WK	Whapmagoostui-Kuujjuarapik
WWR	Window-to-Wall Ratio

Variables		***Units***
ARENA	TRNSYS thermal zone that represents Kuujjuaq Forum's arena	
BSMT	TRNSYS thermal zone that represents Kuujjuaq Forum's basement	
$C_{t,n}$	Net cashflow at the end of the n^{th} year of the study period	CAD (CA$)
GYM	TRNSYS thermal zone that represents Kuujjuaq Forum's gymnasium	
L	Total borehole length	M
N	Analysis time period	Year
n	A time point during the analysis time period	Year
OFF1	TRNSYS thermal zone that represents Kuujjuaq Forum's 1^{th} floor facilities	
OFF2	TRNSYS thermal zone that represents Kuujjuaq Forum's 2^{nd} floor facilities	
$Q_{\mathrm{g,h}}$	Peak hourly ground load (heating)	W
$Q_{b,\mathrm{h}}$	Peak hourly building load (heating)	W
$Q_{\mathrm{g,m}}$	Highest monthly ground load (heating)	W
$Q_{b,\mathrm{m}}$	Highest monthly building load (heating)	W
$Q_{\mathrm{g,y}}$	Yearly average ground load (heating)	W
$Q_{b,\mathrm{y}}$	Yearly average building load (heating)	W
r	Discount rate	
R	Resistance in imperial units	ft²·°F·h/BTU
RSI	Resistance in international units	m°C/W
R_{b}	Effective borehole thermal resistance	m°C/W
R_{6h}	Effective ground thermal resistance corresponding to six hours	m°C/W
R_{1m}	Effective ground thermal resistance corresponding to one month	m°C/W
R_{10y}	Effective ground thermal resistance corresponding to ten years	m°C/W
T_{m}	Mean temperature of fluid in the borehole	°C
T_{g}	Undisturbed ground temperature	°C
T_{p}	Temperature penalty for the interference of adjacent bores	°C

1. INTRODUCTION

Nunavik is a geographically isolated region in northern Quebec, home to about 14,000 inhabitants [1], mostly Inuit and Cree, living in 14 remote communities. These villages are disconnected from the country's main road and energy networks, they rely on their own diesel power plant for electricity production and all buildings are equipped with oil tanks for space heating. The dependence on fossil energy results in significant expenses for power production. The cost of diesel in Nunavik for the 2023-2024 season was 2.12 CA$ /L before subsidy, substantially higher than the Quebec average of 1.61 CA$/L [2]. In 2024, Makivvik Corporation announced a direct subsidy to stabilise diesel cost at 1.84 CA$/L [3].

Energy transition in remote Canadian communities is becoming increasingly important, and is at the core of economic, environmental and social considerations for local governments [4]. Across Canada, 276 remote communities, housing approximately 196,000 people, face similar challenges. Of these communities, 169 are Indigenous with about 113,500 people [5]. Renewable energy technologies, such as wind, solar and geothermal, offer promising solutions for sustainable power and heat production. Transitioning to these alternative sources could allow communities to reduce their carbon footprint, lower energy cost, and enhance energy security and resilience. Geothermal systems in particular hold significant potential for heating buildings in Arctic and subarctic regions, presenting advantages like utilization of an on-site resource for energy, a high capacity factor, long lifetime, low operational cost, and load flexibility [6]. However, due to high capital cost, very few projects and installations are running, and little feedback has been provided. Shallow geothermal systems have been the subject to limited field investigation in the high north. In Fairbanks (Alaska) [7], a horizontal ground loop system, digging down to 9 feet to install the pipes, was connected to a 465 m² (5,000 ft²) building in 2013. Designed for a 17.6 kW heating load, the system demonstrated interesting performance, generating 20,000 to 30,000 kWh of annual heat and avoiding 2650 L (700 gallons) of fuel oil annually. Over the first 8-year operational period, the system maintained a COP averaging 3.0 [8]. The maintenance cost amounts to 300$ every other year and the geothermal system allowed to stabilize electricity cost to 0.24 US$/kWh. A review by Garber-Slaght and Stevens [9] examined 13 GSHP installations in Fairbanks, including horizontal loops and vertical wells (135 to 250 feet), with capacities between 14 and 35 kW (4 and 10 tons). These systems supplied diverse building typologies, covering residential dwellings from 93 to 465 m² (1,000 to 5,000 ft²) surface area, multi-unit condominiums, offices, and educational facility make-up air system. While the study generated useful guidelines for decision-making, the authors emphasized the need for long-term performance data for future system design implementation.

Research over the past decades has demonstrated the viability of shallow and deep geothermal potential in Canadian remote northern communities [10], [11], [12], [13]. In Nunavik, the subarctic climate with ground temperature near the freezing point of water throughout the year makes vertical closed loop circulating antifreeze mixtures the most effective Ground Heat Exchanger (GHE) system.

Several studies have assessed the feasibility and benefits of geothermal and hybrid systems in Nunavik. Belzile et al. [14] simulated an absorption Ground-Coupled Heat Pump (GCHP) with a horizontal exchanger in Kangiqsualujjuaq and demonstrated it could reduce heating oil consumption by 40% compared to conventional systems powered by diesel-generated electricity. Giordano and Raymond [10] showed that a Borehole Thermal Energy System (BTES) assisted with solar thermal panels to heat the drinking water of the Kuujjuaq pumping station could achieve 13% annual oil savings and reduce CO2 equivalent emissions by 19 tons within three years of operation. In Whapmagoostui-Kuujjuarapik (WK), Maranghi et al. [15] found that Solar-Assisted GCHP (SAGCHP) with compression system reduced fuel consumption by 38%, which could be increased to 59% with the addition of batteries. Also in WK, Langevin et al. [16] identified scenarios with compression SAGCHP that could reach 61% greenhouse gas (GHG) savings. Moreno [17] and Moreno et al. [18] highlighted mixed alternatives, like SAGCHP combined with biomass or oil furnace, as promising options that could achieve 50% to 99% of GHG emissions. All studies agreed that SAGCHP remains the most suitable option for reducing carbon emissions in Nunavik and enhancing communities' energy sovereignty. Depending on the efficiency of the diesel power plant, located around 30%, and the heat pump COP, which can be assumed around 3 in Northern conditions, we obtain a 90% efficiency that can be similar to conventional oil furnace or boiler. Hence, assistance from renewable energy is mandatory if we want to reduce GHG emission and have a significant environmental gain.

Despite the promising results, renewable energy development in Nunavik, and in isolated northern regions in general, is also an economical challenge. In such area, drilling cost can represent about to 30-50% of the capital cost of a project. Drilling equipment already present in certain locations, such as Kuujjuaq, is specialized in mineral exploration. Diamond drills used for mineral exploration are more compact than usual geothermal drills, thus easier to transport, but the drilling diameter is narrower and less adapted for GHE. Considering a drilling cost between 50 and 300 CA$/m, Gunawan et al. [11] emphasized that SAGCHP systems can be economically more attractive than oil furnace heating as all the studied scenarios present a relatively fast payback between 3 and 12 years. Moreno et al. [18] identified a promising strategy of net metering, obtaining credits for injecting surplus electricity from solar panels into the grid, to reduce cost and making systems even more economically competitive.

Meyer et al. [19] and Garber-Slaght and Stevens [9] emphasizes the importance of accurate GSHP sizing, highlighting the need for full data on operational buildings in Arctic and subarctic regions. However, a significant literature gap exists and has been mentioned regarding northern building performance [20]. Rouleau and Gosselin [21] monitored ten dwellings, limited to a single building typology (semi-detached), reporting heat demands ranging from 180 to 350 kWh per m² of surface area and a daily electricity consumption between 6.21 and 29.20 kWh. One-year monitoring studies of high-performance demonstration house were conducted in Iqualuit (Nunavut, Canada) [22], Sisimiut (Greenland) [23] and Kiruna (Sweden) [24], [25], but these dwellings were mostly unoccupied, necessitating further research that includes the impact of occupant's behavior. Furthermore, data on non-residential buildings – such as grocery stores, healthcare facilities, and recreational centers –, present in most northern communities, remains even scarcer, accounting for the critical gap in current scientific understanding.

On going to the present report, the study focuses on the Kuujjuaq Forum, an important activity center in Kuujjuaq, which is an Inuit community of 2,700 inhabitants [1] located on the 58° parallel in Nunavik. Climate is characterized by harsh winters, with low temperatures, strong winds, and short days. Average annual temperature is -5.4°C [26], with 8,523 heating degree days below 18 (HDD18) [27]. Recent geothermal tests in Kuujjuaq revealed promising thermal properties, with an average ground temperature of 1.8°C between 15 and 145m and thermal conductivity of 2.67 ± 0.25 W/mK [28], [29]. In Nunavik, the annual average heating demand for a typical dwelling is 310 kWh/m² [30], compared to 145 kWh/m² in southern Quebec [31]. The Forum is also equipped with a monitored PV system, reducing reliance on the local diesel-powered microgrid. This study gathers field data on the Kuujjuaq Forum's heating and electrical demand, alongside its PV production, to assess the feasibility of integrating SAGCHP system. Very limited data on real life building performance in subarctic regions are accessible in literature, especially non-residential buildings. By presenting field data and addressing the technical and economic challenges of sustainable energy transition in Nunavik, the present work contributes to fill the gap of solar PV production and energy consumption data for non-residential buildings in Arctic to subarctic regions.

In this context and in collaboration with the building's owner, Kuujjuamiut Society, the project was initiated to evaluate the potential of SAGCHP system for space heating in the Kuujjuaq Forum. The objective of the project was to assess the energy consumption of this operating building and the solar PV system performance, to ultimately propose additional sustainable energy solutions to meet the heating demands of the building, leveraging both geothermal and solar energy to reduce reliance on diesel. This paper describes the development of a building model to determine the annual heat load profile of such recreation center, size and optimize a GCHP system to meet the demand, and evaluate the potential of a PV system to assist heat pumps. Results are discussed in the energy transition context to provide guidelines for other remote communities of the Arctic facing similar challenges to decreases their fossil fuel consumption.

2. CASE STUDY AND FIELD DATA

The studied building is an existing infrastructure in Kuujjuaq, known as the Kuujjuaq Forum. All the information gathered comes from direct exchanges with the owner, on-site observations and documentation, and an audit carried out in 2022 [32]. The building is run by Kuujjuamiut Society and was built in 1992. The eastern part of the building was added a few years after. It includes offices, a conference room and sports facilities, such as an arena, a gymnasium, and a fitness centre. Changing rooms and showers are also available.

Figure 2.1. Photography of the Kuujjuaq Forum (Societe Kuujjuamiut Inc.).

2.1. Building use

The building total surface area is about 6000 m². It can welcome up to 200 to 300 people per day on most busy days, mainly for sport activities, according to on-site verbal reports. Occupation is important during hockey season and decrease during summer. Kuujjuamiut Society offices are also located in the building, with about 15 people coming to work from Monday to Friday. The Kuujjuaq Forum is open seven days a week, all year long, except for the Christmas holiday. The ice rink runs from September 1st to April 30th. In summer, the arena is used for an annual multiday festival.

Table 2.1 presents the building's annual oil consumption, according to Nunavik Petro Inc. bills, converted into energy demand in MWh using a conversion factor of 10.77 kWh/L for oil [33] and a conventional combustion efficiency of 0.8 for the oil boiler. From 2020 to 2024, an average of 66,922 L of oil was delivered annually, corresponding to an average annual energy consumption of 577 MWh. Figure 2 shows the monthly average oil consumption through the year, converted into heating energy demand in MWh. Oil is used for both space heating and domestic hot water.

Table 2.1. Annual oil consumption, converted in energy units.

Year	Oil delivery (L)	Energy demand (MWh)
2023	69,140	596
2022	51,570	375
2021	70,200	605
2020	76,421	659
Mean	**66,922**	**577**

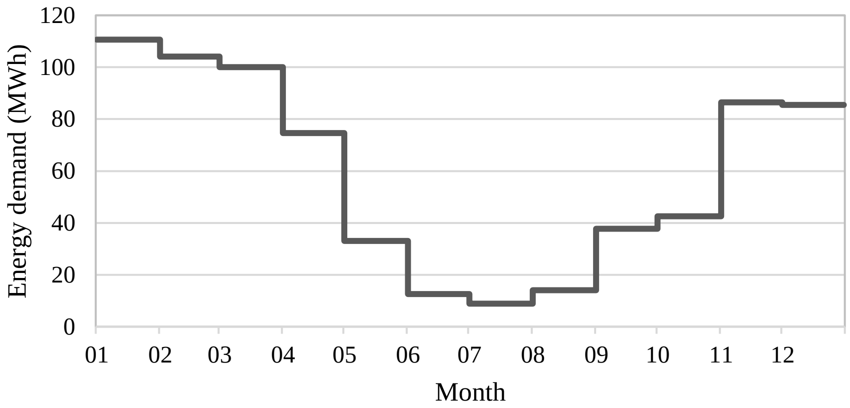

Figure 2.2. Kuujjuaq Forum's average heat demand over the period 2021-2024 (heating and domestic hot water – DHW).

2.2. HVAC system

Two boilers of 268 kW each are located in the building's mechanical room. They run from September to June and supply heating for radiators and ventilation. Radiators work 24 hours per day and ventilation is on from 7:30 to 23:00. Several air handling systems supply the different spaces (gymnasium, changing rooms, washrooms, hall and offices, etc.). Air handlers in the old part of the building do not have exhaust ducts. Hence, incoming fresh air is balanced by conditioned air leaving the building via leakage or exhaust fans without energy recovery. In building's addition section, air handlers have an intake, an exhaust and a mixing damper. All air handlers have an outdoor air intake. The building is not equipped with central air conditioning. Few window-mounted units are installed and removed seasonally. Two 190-liter oil-fired tank heaters supply domestic hot water. The ice rink chiller system includes two 60-hp compressors and two 20-hp brine pumps. Heat rejected by the chiller system is used to heat arena's ventilation system. Air flows in the main ducts were estimated from commissioning documents and audit [32] and are given in Table 2.2. With these values, the outdoor air ratio (OA) for ducts 1 (gymnasium), 2 (first floor) and 4 (second floor, entrance hall, and first floor office) are, respectively, 16 %, 14 % and 15 %. We also know that air flow rates are sometimes adjusted manually during the year for comfort purposes.

Table 2.2. Return air, outdoor air (OA) and exhaust air flows measured in the Kuujjuaq Forum's HVAC system.

Duct ID	Space	Type	Flow (L/s)
1	Gymnasium	Supply	3,500
		Return	1,570
		Outdoor air	570
		OA ratio	*16 %*
2	First floor (changing rooms, washrooms, etc.)	Supply	1,950
		Return	1,060
		Outdoor air	280
		OA ratio	*14 %*
3	First floor washrooms and showers	Exhaust	2,000
4	Second floor (offices, corridors), entrance hall, first floor office	Supply	1,300
		Return	950
		Outdoor air	200
		OA ratio	*15 %*
5	Second floor washrooms	Exhaust	300
6	Mechanical and electrical room	Supply	1,600
		Outdoor air	Unknown*
7	Arena	Supply	5,700
		Exhaust	5,300
		Outdoor air	Unknown*
8	East addition	Supply	2,000
		Outdoor air	Unknown*

* Indicated as "minimal" or no information in the documents

2.3. Existing solar PV system

As seen in Figure 2.1, the case study building is equipped with a PV system that was installed and commissioned in 2021 and is running at its full capacity since May 2023. The installation is composed of six inverters (17.5 kW and 15 kW), each one connected to four series of 16 modules (335 kW; Canadian Solar CS1H-335MS [34]). The total PV surface is about 648 m², and electricity production can be either directly use by the building or sent to the local micro-grid. Electrical use is monitored, and daily reports can be accessed with data on the building's electricity consumption, the electricity production from PV system that is used by the building, the PV production that is exported to the grid, and building's electricity consumption from the grid. In Figure 3.7, we can see the daily energy balance profile from January 1st 2023, to October 21st 2024, considering that the PV system only started to run at its full capacity on May 1st 2023. A clear demarcation of electricity use is visible between the summer and winter periods, corresponding to the operation of the ice rink and heating system. As reports provide daily data, we can see that on some days PV production was both used by the building and exported to the grid. During those days, electricity was exported to the grid when PV production exceeded building's electricity needs. Over the studied period, the Kuujjuaq's Forum total electricity needs amounted to 1006.92 MWh, of which 133.63 MWh were provided by the PV system and the rest were provided by the grid. The PV system produced a total of 164.24 MWh, 30.61 MWh were sent to the grid. In total, 81% of renewable energy produced by solar panels were used instantly on site and this production enabled the building to be self-sufficient for 13% of its total electricity needs.

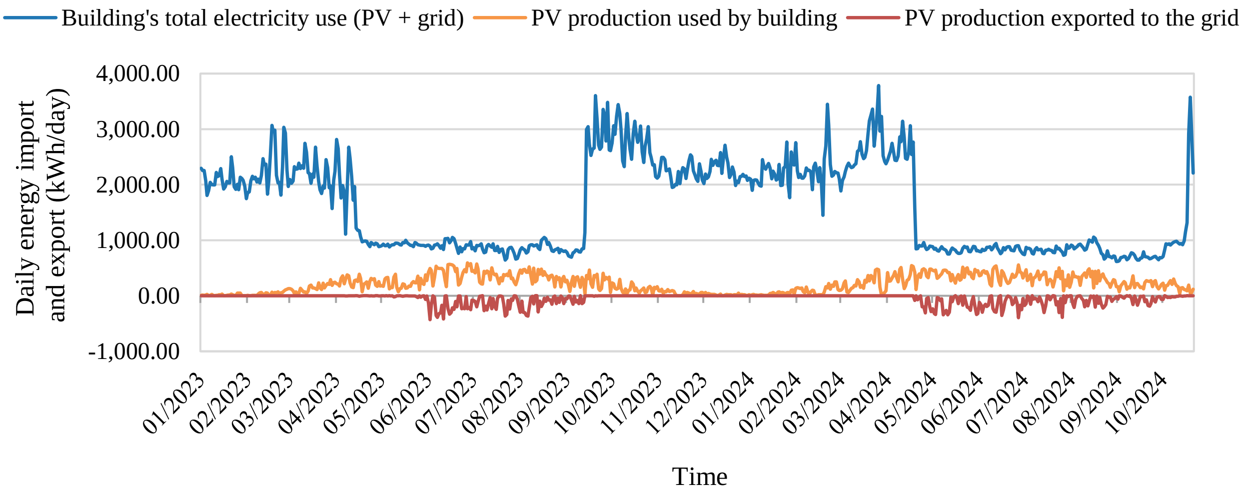

Figure 2.3.Kuujjuaq Forum's daily electricity energy balance over time (2023-2024).

3. METHOD

3.1. Heating load estimation for domestic hot water

Consumption data obtained from oil bills include space heating and DHW. As ground-source heat pumps can hardly supply 100% of a building's thermal load, this study focuses on space heating, and the energy demand associated with DHW has been estimated to be subtracted from the heating load profile.

In the Forum, DHW is used for washrooms and showers, and for ice rink surfacing. For washrooms and showers, we estimate 40 users per day, who would each use the shower once and the sink for hand-washing twice, consuming 7 gallons and 0.2 gallons of hot water respectively, i.e. 616 gallons per day. Assuming 20 days per year when the building is closed (holidays) or at very low attendance rate and that the building occupancy is reduced by half outside the hockey season, the energy demand for showers and washrooms is estimated to 25 MWh per year. One ice rink resurfacing consumes approximately 100 gallons, and we assume five resurfacings per day during the hockey season, lasting from September to April. Hence, the energy demand for ice rink resurfacing would be 27 MWh per year. The total energy demand for DHW is estimated to 52 MWh per year, i.e. 9% of the total energy use for heating. Figure 3.1 shows the average monthly load profile of Kuujjuaq Forum, including the estimation of heating load for DHW.

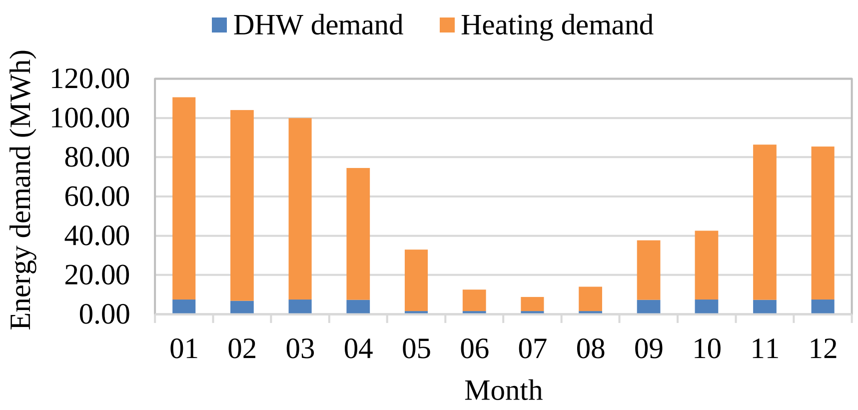

Figure 3.1. Monthly heating demand including estimated consumption for DHW and remaining consumption for radiators and ventilation.

3.2. Building model and heating load profiles

Five distinct thermal zones were created using Sketchup 3D design software: arena (ARENA), gymnasium (GYM), 1st floor facilities (OFF1) including offices, changing rooms, washrooms and shower, 2nd floor facilities (OFF2) including offices, conference rooms and washrooms, and eventually basement (BSMT) where the electrical and mechanical rooms are located. The building shape was simplified, respecting the window-to-wall ratio (WWR) for each orientation. Building's windows are low-E double-glazed, except for the eastern part where they are low-E triple glazed, giving a ratio of 17/83 between double and triple glazing, respectively. The total surface floor area is 5,892 m². The structure was imported in the building energy software TRNSYS 18 using the plugin TRNSYS 3D and Type56 unit. Figures 3.2 and 3.3 shows 3D views and footprint of the building model. The annual heating load was modelled using Kuujjuaq weather data and known building characteristics (Table 3.1).

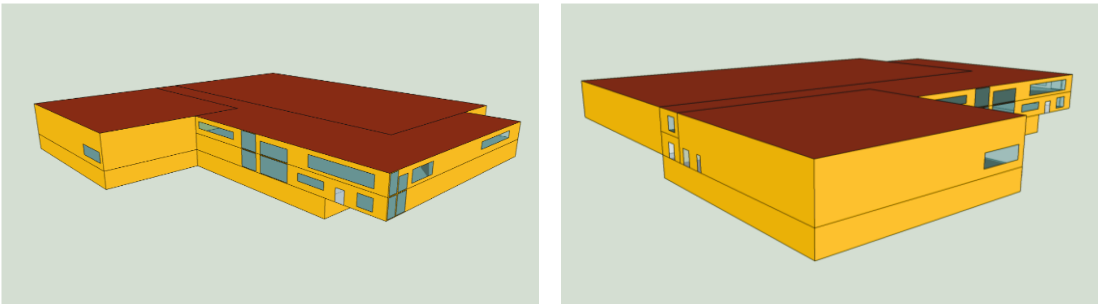

Figure 3.2. 3D Views of the Forum's Sketchup simplified model.

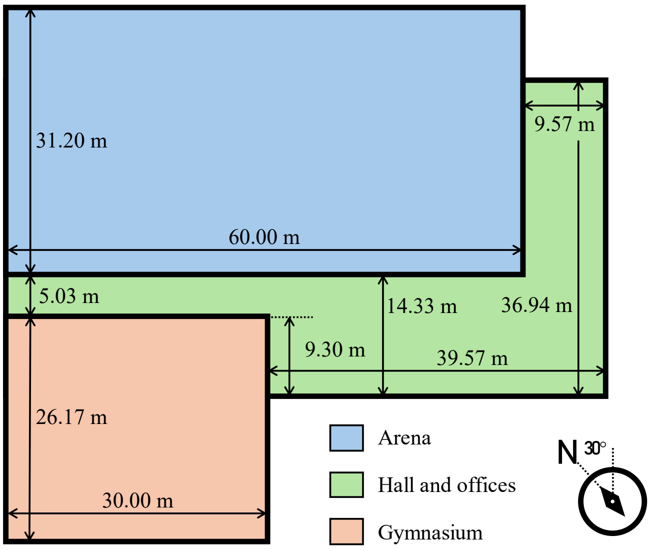

Figure 3.3. Sketchup simplified building's first floor footprint, dimensions and orientation.

Table 3.1. Forum's thermal envelope and HVAC system characteristics.

Parameter	Value	Units
Thermal envelope		
Walls thermal resistance	RSI 4.22 (R 24)	m²·K/W (ft²·°F·h/BTU)
Roof thermal resistance	RSI 7.22 (R 41)	m²·K/W (ft²·°F·h/BTU)
Fenestration U-value		
Double glazing	1.36	W/m²·K
Triple glazing	0.88	W/m²·K
Window-to-wall ratio		
North	0.0	%
West	0.7	%
South	19.5	%
East	11.5	%
HVAC System		
Ventilation	Multiple zones with outdoor air supply and heating	
Heating	Boiler powered water-glycol loop (heating coils for ventilation and hydronic baseboard)	
Cooling	None	
Domestic hot water	Boiler powered water-glycol loop	

The maximum capacity of the heating system was set to 536 kW, equivalent to the two boilers of 268 kW each. Schedules were defined for occupation, ventilation, lighting, equipment and heating. Data from the electrical room provided us information on the daily average electricity consumption, which was 2,255 kWh/day during the 2023 to 2024's winter and 988 kWh/day for 2023 summer. These electrical loads include the electricity used for ventilation and heating equipment, such as fans and pumps. Thus, these values were used to calculate internal loads from lighting and equipment. Electric loads were distributed proportionally between thermal zones, based on floor area, zone type (office, sport center, mechanical room) and standard values for internal load taken from Chapter I.1 of the Quebec Construction Code.

In the present project, we focused our model design and our analysis on the heat demand from the ventilation system. The arena has its own air heating system supplied by waste heat from the ice rink compressors and it is not taken into account in our analysis. Hence, we only considered heating demand for GYM, OFF1, OFF2, and BSMT's ventilation systems. Supply air flow rates from Table 2.2 were used as input. Air flow n°9 that serves building's east addition was evenly split and added to OFF1 and OFF2's air flow. Table 3.2 sums the supply air flow rates for each TRNSYS zone. The ratio of outdoor air to the total air supply and the infiltration rate was adjusted to match with the real data from oil delivery bills.

The ventilation model is divided into two parts: preheating system and terminal heating system. The aim of this system is to bring air at room temperature, i.e. 20°C. Air heating system is modeled with Type 670 "Heating coil with hot-side bypass to keep air-side outlet below setpoint". The preheating setpoint temperature is 5°C. Then, preheat air is mixed with air return from the thermal zones and the terminal temperature setpoint is fixed to 20°C for all zones, except the basement at 14°C. In this configuration, the heat production source does not need to be specified in the software. The entire heating capacity, within the imposed 536 kW limit, is used to reach the 20°C setpoint. Figure 3.4 shows model's layout in the software.

Table 3.2. Forum air handlers' characteristics: spaces delivered and air flow rate supplies.

Duct ID	TRNSYS Thermal zone	Total air supply rate
1	GYM	3,500 L/s
2, 8	OFF1	2,950 L/s
4, 8	OFF2	2,350 L/s
7	ARENA	5,700 L/s
6	BSMT	1,600 L/s

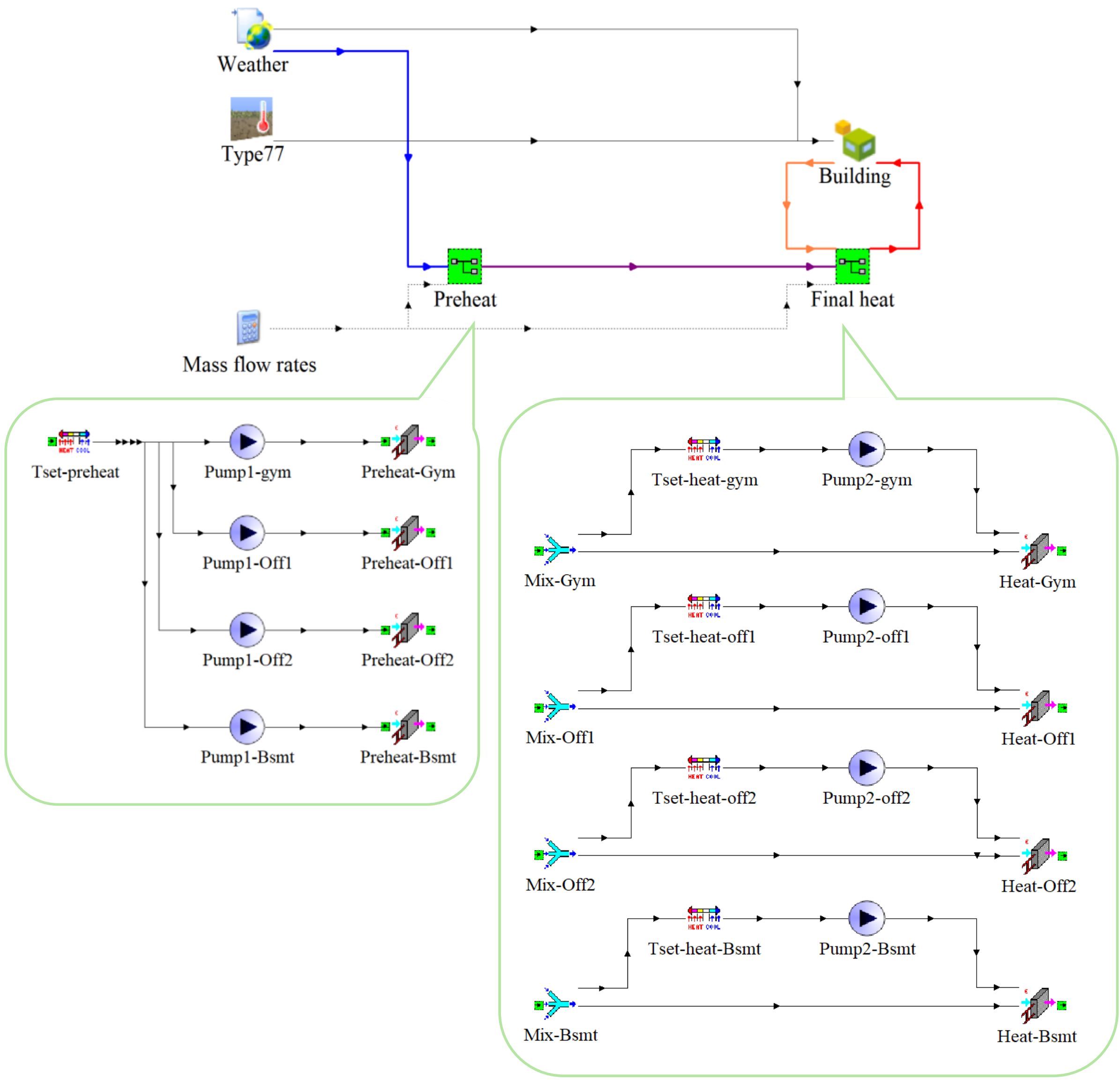

Figure 3.4. Building model's layout in TRNSYS 18.

3.3. Geothermal heat pump (GHP) sizing and modelling

Different load profiles for ventilation heating were then used to size the borefield made of closed-loop GHEs: total ventilation heating load (preheating and terminal heating), preheating load only (about 70% of the total air heating load) and terminal heating only (about 30% of the total air heating load). We assume that the remaining heating demand is met by the existing oil boiler system. Borehole sizing was executed with the software Versa GLD [35]. This software uses Bernier equation [36] to estimate the total length of the borefield:

$$L = \frac{Q_{\mathrm{g,h}}\,R_{\mathrm{b}} + Q_{\mathrm{g,y}}\,R_{10\mathrm{y}} + Q_{\mathrm{g,m}}\,R_{1\mathrm{m}} + Q_{\mathrm{h}}\,R_{6\mathrm{h}}}{T_{\mathrm{m}} - (T_{\mathrm{g}} + T_{\mathrm{p}})} \quad \text{(Eq. 1)}$$

where L (m) is the total borehole length; $Q_{g,h}$, $Q_{g,m}$, and $Q_{g,y}$ (W) are, respectively, the peak hourly ground load, the highest monthly ground load, and the yearly average ground load (heating); R_b (m°C/W) is the effective borehole thermal resistance, calculated according to the multipole model [37]; R_{10y}, R_{1m}, and R_{6h} (m°C/W) are, respectively, the effective ground thermal resistance corresponding to 10 years, one month and six hours ground loads, calculated according to the finite line source equation [38]; T_m, T_g and T_p (°C) are, respectively, the mean temperature of fluid in the borehole, the undisturbed ground temperature, and the temperature penalty for the interference of adjacent bores.

Different parameters like heat load, borehole design, heat pump inlet maximum temperature, and number of boreholes were assessed to study the impact on the borehole depth. Space between two boreholes is set to six meters. Table 3.3 summarizes the different scenarios tested. Borehole designs were based on drill rigs commercially available in Kuujjuaq. A heat pump with a working range adapted to the cold temperature of the North was used. ASHRAE's *Geothermal Heating and Cooling* guide [39] recommends a source-side Entering Fluid Temperature (EFT) between 6°C to 11°C below average ground temperature. Knowing that conventional heat pumps operate down to approximately -7°C, we choose two different operating scenarios to stay in a conservative approach: -3°C and -5°C as a limit for EFT. Three different heat load scenarios were also tested: total ventilation heating load, only air preheating load, and only air terminal heating load. The building loads $Q_{b,h}$, $Q_{b,m}$, and $Q_{b,y}$ for each scenario were calculated according to simulation results and are detailed in Section 4.1. $Q_{b,h}$, $Q_{b,m}$, $Q_{b,y}$ are, respectively, the peak hourly heating load, the highest monthly heating load, and the yearly average heating load of the building. Versa GLD uses these values as input, with HP's COP and minimum HP inlet temperature, to estimate ground loads in Eq. 1.

Table 3.3. Scenarios for borehole sizing [12].

	Design 1 "Standard"	**Design 2 "High efficiency"**
Borehole design scenario		
Nominal tube size (in)	¾	1 ¼
Borehole diameter (mm)	75.4	95.8
Pipe internal diameter D_{in} (mm)	27.0	34.0
Pipe external diameter D_{ext} (mm)	33.4	42.2
Operating scenario		
Minimum HP inlet temperature (EFT ; °C)	-3°C	-5°C

The obtained borefield length estimations were then used as an input value for the GHP system model in TRNSYS 18. Figure 3.5 shows the model's layout in the software and Table 3.4 describes the input parameters for the geothermal system. The "high efficiency" design from Table 3.3 was used for borehole dimensions. A scaling factor SF is used to simulate several heat pumps connected in parallel. In this model, the scale factor at each time step according to the following equation:

$$SF = \frac{\dot{m}_{\text{fluid}} * Cp_{\text{fluid}} * (T_{\text{load,in}} - T_{\text{load,out}})}{Q_{\text{rated heating}}} \quad \text{(Eq. 2)}$$

where $\dot{m}_{\text{fluid}}$ is the mass flow rate of the heat carrier fluid of the load side, Cp_{fluid} is the fluid heat capacity, $T_{\text{load,in}}$ et $T_{\text{load,out}}$ are respectively the entering and leaving fluid temperature, and $Q_{\text{rated heating}}$ is the rated capacity of the heat pump.

The maximum SF value over the simulation time indicates the minimum number of heat pumps in parallel required to fulfill heating demand. This factor can be reduced if the used heat pumps have a higher rated heating capacity.

Table 3.4. GSHE system main input parameters in TRNSYS 18.

Characteristic	**Value**	**Unit**	**Reference**
Vertical U-tube ground heat exchanger **Type 557**			
Borehole depth	*Defined with VersaGLD*		
Number of boreholes	*Defined with VersaGLD*		
Ground thermal conductivity	2.67	W m^{-1} K^{-1}	[28]
Ground specific heat capacity	2,358.00	kJ m^{-3} K^{-1}	[12]
Ground density	2,620.00	kg m^{-3}	[28]
Average ground temperature	1.80	°C	[28]
Amplitude of surface temperature	36.50	°C	[26]
Grout thermal conductivity	1.50	W m^{-1} K^{-1}	[12]
Tube thermal conductivity	0.40	W m^{-1} K^{-1}	[12]
Fluid’s percentage of propylene glycol	25.00	%	
Fluid specific heat	4.02	kJ kg^{-1} K^{-1}	Versa GLD tables
Fluid density	1,031.00	kg m^{-3}	Versa GLD tables
Water-to-water heat pump ***Type 927***			
Source and load fluid specific heat capacity	4.02	kJ kg^{-1} K^{-1}	Versa GLD tables
Source and load fluid density	1,031.00	kg m^{-3}	Versa GLD tables
Rated liquid source and flow rate per HP	0.40	L s^{-1}	TRNSYS 18 default value
Rated heating capacity	30,000.00	kJ h^{-1}	TRNSYS 18 default value

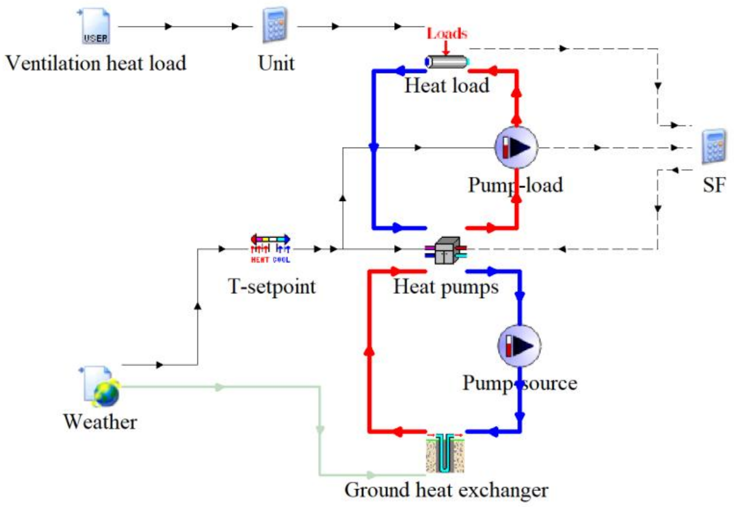

Figure 3.5.Ground-coupled heat pump system's layout in TRNSYS 18.

3.4. SAGCHP system sizing and modelling

As mentioned earlier, increasing buildings' electrical load with heat pumps powered by diesel power plant can be counterproductive. The use of geothermal heat pumps in Northern Canada is only worthwhile if they are at least partly powered by a renewable energy source, like solar energy. When designing a SAGCHP in a remote subarctic region relying on diesel for electricity generation, it is important to determine the project's viability by evaluating the potential of meeting the electricity demand of the heat pumps with the PV system. The Kuujjuaq forum is already equipped with a PV system of approximately 648 m², installed on a part of the roof. To study the production of the PV system over one-year, we treated solar data as follows and as we can see on Figure 3.7 "Current PV panels" profile: January 1st to April 30th is 2024 data, as the system was not at its full capacity in 2023; May 1st to October 21st is the mean of 2023 and 2024 data; and October 22nd to December 31st is 2023 data, as 2024 data were not yet available. Our model assumes that the current PV production from the existing system remains dedicated to the building's existing electrical consumption and is not allocated to the GCHP. As shown in Figure 3.6, an aerial photograph of the Forum, the PV panels currently occupy a fraction of the roof, designated as Zone 1 (Z1). To increase the renewable energy available for powering a GCHP system, we propose installing additional PV panels on the unused roof area, designated as Zone 2 (Z2). The current used area Z1 is approximately 1,110 m², with a panel occupation ratio of 0.58. Based on this ratio, we estimated that unused area Z2, which represents around 2,370 m², could accommodate an additional 1,385 m² of PV panels – approximately 2.14 times the currently installed area. Using the power intensity (kWh/m² produced) of the existing system in 2023 and 2024, we can calculate the estimated production profile for the additional panels on Z2 for the same period, as represented in Figure 3.7 "Additional PV panels" profile. These production profiles are based on the Fronius reports and have a daily time step that neglect potential mismatch during the day, as we saw in Section 2.3 (Figure 2.3). PV production at peak during midday may exceed HP needs but fail to meet HP requirements during evening or night. To address this, we simulated the system in TRNSYS, allowing for finer time step and better accounting for these mismatches. Table 3.4 details the parameter input used in Type 103 unit "Photovoltaic Array". The simulated PV production from TRNSYS model has been adjusted to reach the lowest Root-Squared Mean Error (RSME) compared to "Additional PV panels" profile. Result is plotted in Figure 3.7, under "TRNSYS PV panels model" label. The final aim is to use the modelled profile to evaluate the solar energy penetration, or solar energy coverage, of the additional system. The penetration *P* represents the fraction or percentage of energy demand of a building covered by solar energy. In this case, the energy demand considered is the ventilation preheating load.

Figure 3.6. Aerial photograph of the Kuujjuaq Forum. Z1 is the dedicated zone for actual solar panels system and Z2 is the remaining available roof surface.

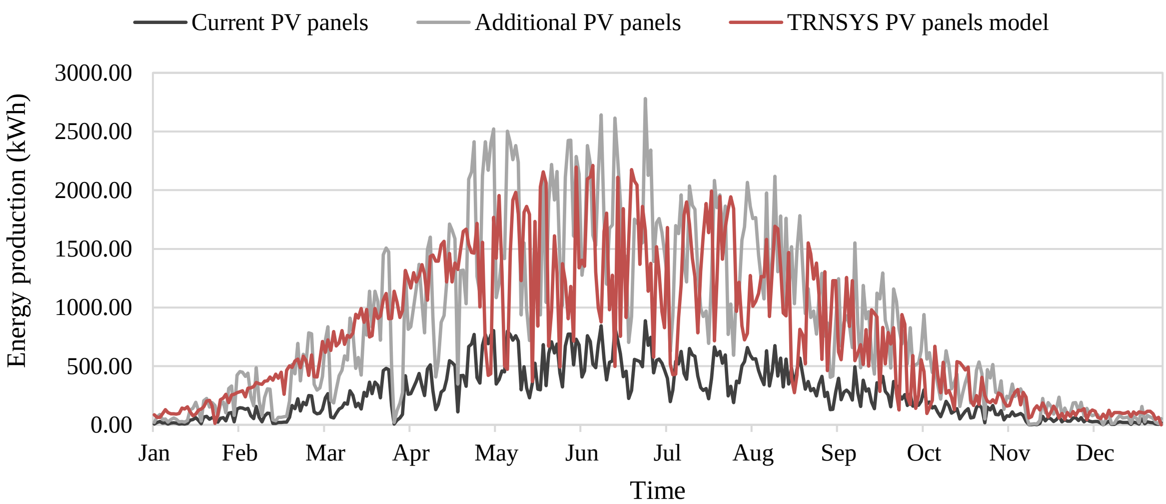

Figure 3.7. Energy production profiles for current PV system, theoretical additional PV system and TRNSYS PV system model.

Table 3.4. PV system main input parameters in TRNSYS 18.

Characteristic	Value	Unit	Reference
Photovoltaic Array **Type 103**			
Module area	1.69	m²	[34]
Number of modules in series	16	-	
Number of modules in parallel	75	-	
Shor-circuit current*	9.72	A	[34]
Open-circuit voltage*	44.3	V	[34]
Current at maximum power point*	8.96	A	[34]
Voltage at maximum power point*	37.4	V	[34]

*at reference conditions

3.5. GHG emissions and costs analysis

Ultimately, we wanted to study the impact of such a new SAGCHP system, and compare the amount of emissions emitted, in tons of CO_2 equivalent (tCO_2eq), and the cost for two cases. The first scenario (Case 1) is the current real-life state which is the building with solar panels, and the second scenario (Case 2) is the proposed SAGCHP system with additional solar panels on the entire roof. We assume an efficiency of 80% for Forum's oil boiler, 30% for power plant generators, and a COP of 3.44 for the heat pumps according to the simulations. For GHG emissions analysis, an emission factor of 2.65 $kgCO_2e/L$ were chosen for oil used by space heating and by the local power plant [33]. For economic analysis, we followed the approach of Moreno et al. [18] and Gunawan et al. [11] by calculating the Net Present Cost (NPC). The NPC represents the current value of all future costs from a project over its lifetime, and it was chosen to evaluate and compare the different scenarios over a period of 25 years. Considering the initial investment costs and the annual cashflow with recurrent and operational costs, it is calculated as followed:

$$NPC = \sum_{n=0}^{N} \frac{C_{t,n}}{(1+r)^n} \qquad \text{(Eq. 3)}$$

where N is the analysis time period (years), n is a time point during the time period (year), $C_{t,n}$ is the net cashflow at the end of the n^{th} year, and r is the discount rate (6% [40]).

In this report, the cashflow only considers costs expenses, so the result will be a negative value that highlights the least expensive scenario. Energy costs considered for the study are the unsubsidized rates, meaning that it does not represent an individual cost to consumers, but rather a general societal cost. Electricity real production costs in Kuujjuaq is approximately 0.86 CA$/kWh before subsidy [41], and heating oil unsubsidized cost was considered 2.13 CA$/L [2]. For the capital cost, we assume that the purchase of equipment includes new equipment as well as the replacement of old equipment. Table 3.5 summarizes the lifetime and the purchase cost for each equipment. For shipping, we applied the rates of NEAS cargo shipping company of approximately 572.25 CA$/ton [42]. The weights considered were:

127 kg for an oil tank [43], 225 kg for a heating oil boiler [44], 300 kg for GSHP [18], and a weight ratio of 15 kg/m² was assumed for solar panels. The installation costs were calculated considering the installation time of each equipment and the average hourly wage for a technician in Kuujjuaq (36.87 CA$/h [45]). Installation time on site is estimated to be 8 h for the oil tank, 16 h for the heating oil boiler, and 16 h for the heat pump. The installation price for PV panels is included in the purchase cost of the equipment. The price of drilling in Canada's North is subject to many uncertainties, so we first considered a worst-case scenario with a cost of 300 CA$/m [11], [18], including labour and heat exchanger pipes. For solar panels price and installation costs, values vary from 2.65 to 3.42 CA$/W in Quebec [46]. We considered a higher price of 5$/W for Kuujjuaq, due to the remoteness [18]. The aim would then be to assess at what price point drilling or solar panels would become economically attractive. Maintenance cost is assumed to be 4.4 CA$/m²/year of the building for the heating oil boiler [47], 1.34 CA$/m²/year of the building for the GCHP [47], and 200 CA$/year for the solar panels.

Table 3.5. Price and lifetime of equipment used in the economic analysis.

Equipment	Lifetime (year)	Purchase cost (CA$)	Reference & remarks
Oil tank	25	2,307	[18], [43]
Heating oil boiler	15	5,279	[18], [44]
GCHP	25	3,595	[18], [47]
Drilling	-	3,060,000	[11], assuming a GHE total length of 10,200 m
PV panels	25	1,100,000	[18], [46], price includes installation

4. RESULTS

4.1. Building's heating load profiles

The TRNSYS 18 energy simulation of the building gives an annual load of 518,827 kWh for space heating only (ventilation and radiators, excluding DHW), corresponding to an energy intensity of 129 kWh/m². The considered area includes spaces heated with boiler only, the arena area which is heated by heat recovery is excluded. Adding the estimate energy consumption for DHW, the total annual heat load amounts to 574,286 kWh (143 kWh/m²), close to the real mean observed of 576,811 MWh. The value of 143 kWh per m² of heated surface area is lower than other values from previous studies showing a heating demand between 180 kWh/m² and 350 kWh/m² in Nunavik [20], [21]. This discrepancy may be due to uncertainties over actual Forum's consumption (possible missing bills), and to the fact that the literature values relate to a different building typology, the semi-detached residential buildings. Figure 4.1 overlays the annual profile generated by the model onto the actual annual profile obtained with oil bills. Parameters like the infiltration rate or flow rate of outdoor air intakes were used to adjust the heating load profile in order to get closer to the observed data. Optimal fitting is obtained with an infiltration rate of 0.4 air change per hour and outdoor air ratio of 18% for GYM, 16% for OFF1, 16% for OFF2, and 10% for BSMT. Again, remaining gaps may be caused by uncertainties in invoices (delivery date, missing bills, etc.).

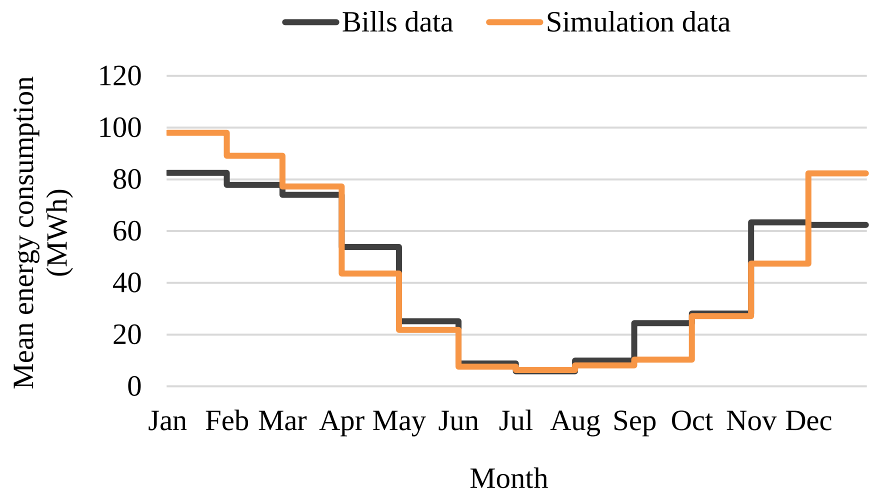

Figure 4.1. Monthly mean energy consumption for space heating (ventilation and radiators) from bills' data and model's simulation.

Table 4.1 presents the energy consumption for each step of ventilation heating and for each thermal zone. Figure 4.2 details the heating demand month by month over the year. We can observe that the heating load from air preheating is significantly higher than the load from terminal heating, particularly in winter. The gymnasium is the zone that requires the most heating, as it has the highest air flow rate. For the basement, the preheating and mixing with the hot return air is enough to bring air temperature to the set point of 14°C. Thus, terminal heating for this thermal zone is negligible.

Table 4.1. Total air heating, preheating and terminal heating loads for each thermal zone of the building for one year simulation.

Zone	**Air preheating (kWh)**	**Air terminal heating (kWh)**	**Total air heating (kWh)**
GYM	102,727	48,927	151,654
OFF1	76,964	38,399	115,363
OFF2	60,788	25,700	86,488
BSMT	27,720	0	27,720
Total	**268,200**	**113,026**	**381,226**

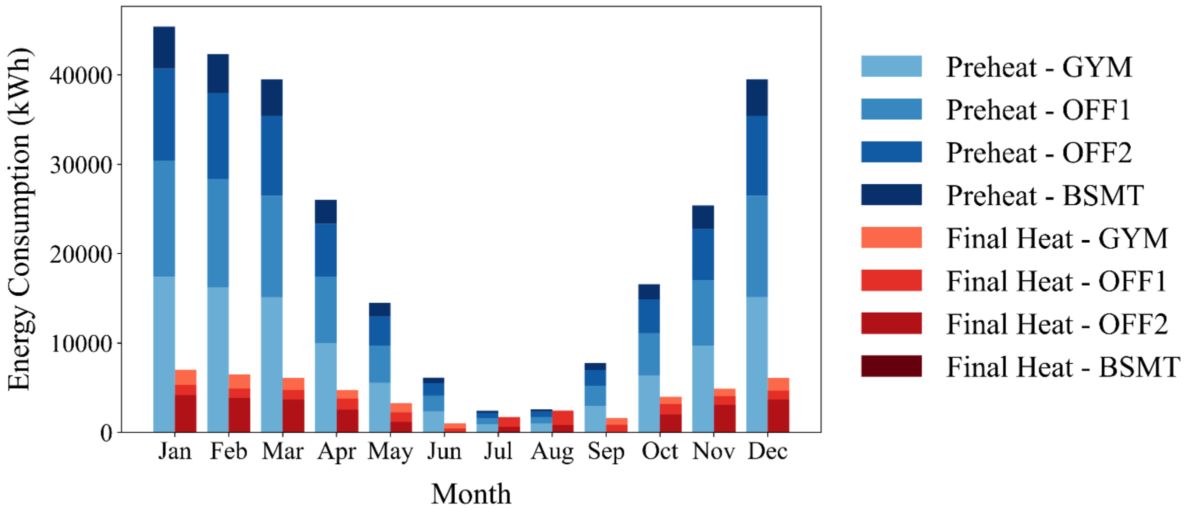

Figure 4.2. Energy consumption by thermal zone for air preheating and terminal heating.

Table 4.2 presents the Kuujjuaq's Forum loads for air heating, with the peak hourly heat load $Q_{b,h}$, the highest monthly heat load $Q_{b,m}$, and the yearly average heat load $Q_{b,y}$. These values are extracted from the air heating profile and are used as input in Versa GLD to size the borefield. Air preheating load and terminal heating load account respectively for approximately 70% and 30% of the total air heating load. In the next section, the three following heat loads are considered for GHE sizing: the total ventilation load, only air preheating, and only air terminal heating.

Table 4.2. Peak hourly building load $Q_{b,h}$, highest monthly building load $Q_{b,m}$, and yearly average building load $Q_{b,y}$ for each heat load scenarios.

Building load scenario	$Q_{b,h}$ (kW)	$Q_{b,m}$ (kW)	$Q_{b,y}$ (kW)
Total ventilation load	108	83	44
Air preheating load	76	61	31
Air terminal heating load	32	22	13

4.2. GHP sizing and performance

Figure 4.3 illustrates the required borehole depth to meet the ventilation heat demand, according to the number of boreholes, the fraction of heat load covered, the borehole design, and the maximum ground fluid temperature accepted in the heat pump. As a reminder, the "-5°C inlet temperature" scenarios are close to the lower operational limit or conventional heat pumps, while the "-3°C inlet temperature" scenarios provide a more conservative approach. Sizing solutions were generated using Versa GLD, with target depths between 150 and 200 m. The results indicate that the borehole design has a minor impact on the required depth, whereas the inlet fluid temperature significantly influences the borehole depth needed to meet the loads.

Results for the different heat load scenarios are:

- Air preheating load: System with more than 40 boreholes and a minimum depth of 200 m can meet the load, regardless of the inlet fluid temperature. With 40 boreholes of 200 m, the total borehole length represents 8,000 m.
- Terminal air heating: A smaller borefield with fewer than 20 boreholes of 200 m or less is sufficient. In these conditions, the total borehole length does not exceed 4,000 m.
- Total air heating: Meeting the load requires significantly deeper boreholes if we choose an inlet temperature limit of “-3°C”. Pushing the system to a limit of “-5°C” allows having a borehole depth closer to feasible levels while meeting the heat demand. A minimum of 40 boreholes is required not to exceed 200 m depth.

Considering a 6 meter-space between boreholes, the borefield area remains compact and under 2,000 m² in all scenarios (except “Total air heating | -3°C”) and would fit within the parking lot area in front of the building.

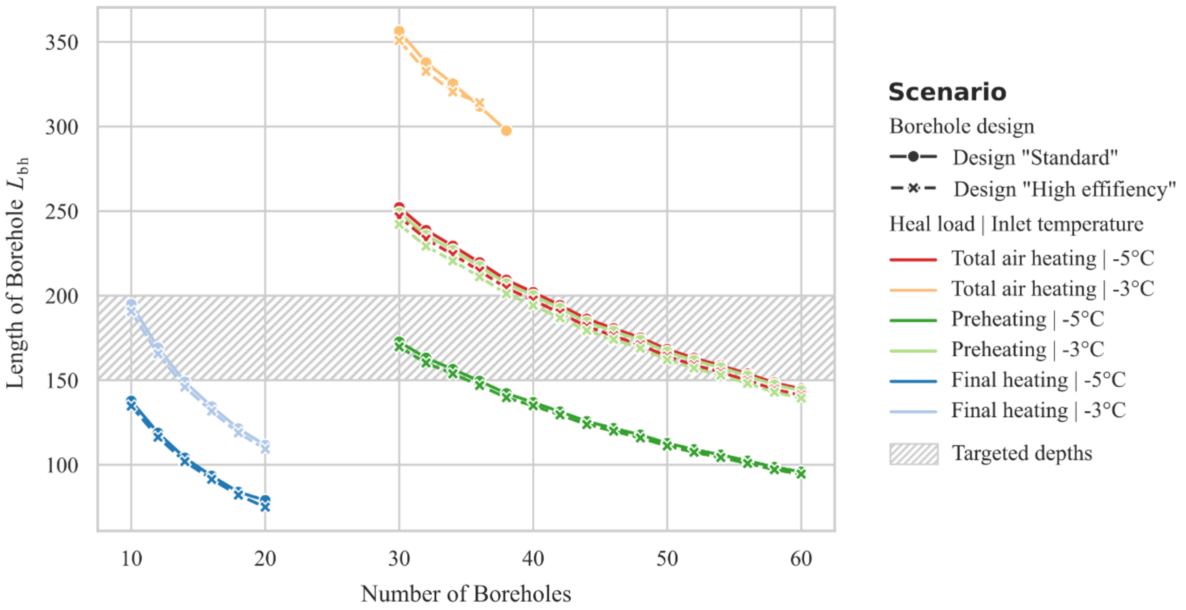

Figure 4.3. Borehole depth according to the number of boreholes, the heating load covered, the borehole design, and the maximum heat pump inlet temperature accepted.

For the next stage of analysis, the more realistic scenario was considered: the GCHP system supplies the air preheating demand, accounting for approximately 70% of the ventilation total heating load and 47% of the total heat demand (ventilation, radiators and DHW). We assume that the terminal heat demand is met with the oil boiler. TRNSYS 18 was used to evaluate GCHP operation over a 25-year dynamic simulation. In Figure 4.4, different borefield size are compared to evaluate the viability of the system. For depth ranging from 150 to 200 m, 60 boreholes are required for viable operations, ensuring that the EFT remains above the operational limit of -7°C for conventional heat pump. For all size scenarios, heat pump system achieved an annual energy consumption of 77,980 kWh, with a mean

COP of 3.44 ± 0.09 and reaching a total capacity of 88.30 kW. On Figure 4.5, we can see that the heat transfer from GCHP system still matches the air preheating load over the 25th year of simulation, and for every 30-minute time steps the load is fully met.

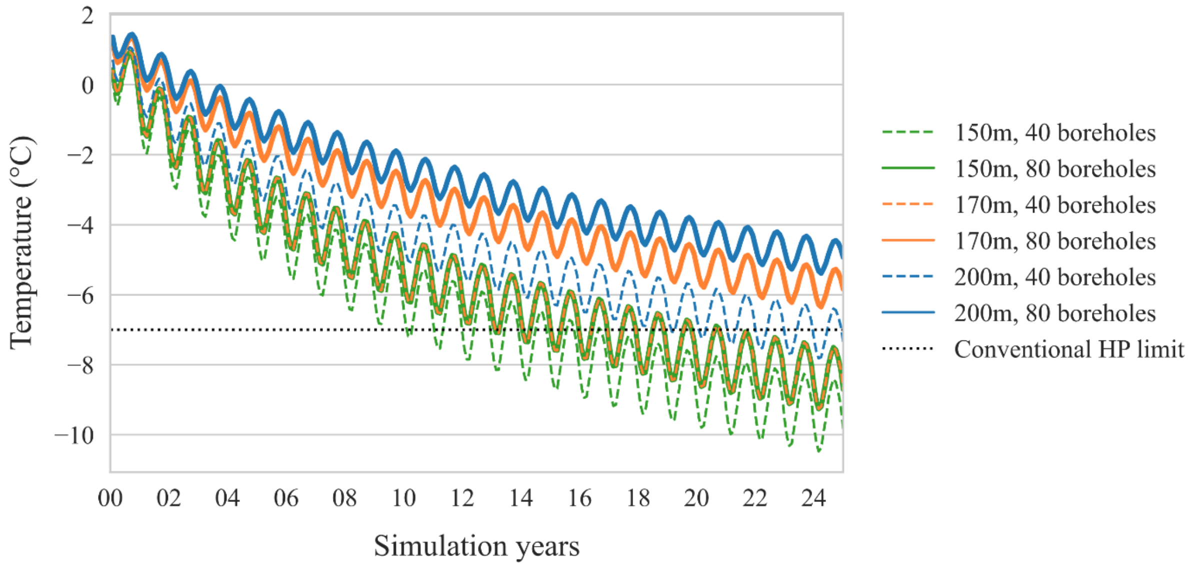

Figure 4.4. Evolution of EFT when supplying the preheating load and considering different GHE size. The "150m, 80 boreholes" and "170m, 80 boreholes" lines overlap.

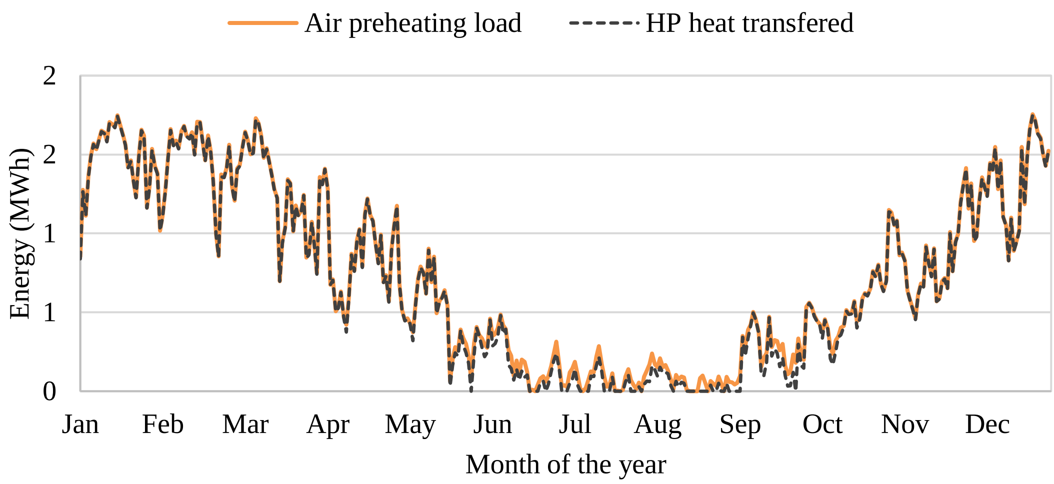

Figure 4.5. Geothermal heat pump heat transfer (24-hour time-step) and air preheating load over the last year of the 25-year simulation, from building and SAGCHP model.

4.3. SAGCHP system sizing and performance

Results from the previous section demonstrate that preheating air with GCHP can be a viable option for the Forum. The next step is to assess if the heat pump electrical demand can be met by the proposed PV system addition. As explained in Section 3.3, this study assumes that the current building's own consumption from the PV system remains the same, and only the new theoretical panel area is used to meet the GCHP electricity demand. The simulation time step was set to 30 minutes. Figure 15 exposes the result of the simulation, with the GCHP system daily energy consumption and the PV system daily energy production. As expected, there is a gap between the heat pump needs and the solar energy production during the winter period. On the opposite, in summertime, PV production largely exceeds the heat pump needs. This production-demand mismatch is common at high latitudes and has already been mentioned in previous papers [48]. During one simulated year, the modelled PV system produces 192.94 MWh, of which 23.77 MWh are used to supply the GCHP. Mean monthly penetration values above 50% can be observed from April to July, with a peak value of 60% in May. Overall, results in Table 4.3 show a penetration of 22% during winter (December to February), 52% during early spring (March to May), 58% during spring (June), 45% during summer (July to September) and 29% during fall (October and November; seasons were defined according to Itulu [49]). Even during wintertime when the heat load is the highest, but the solar irradiance is at its lowest, the PV system is still capable of meeting a significant fraction of the GCHP electricity demand. Increasing the solar power on the roof comes with an increase of exceeds of energy, as we can see on Figure 4.7, going from 15,810 kWh surplus in the current real life to 184,970 kWh in the proposed scenario. The issue of the mismatch between renewable energy production and energy demand in buildings is a real challenge in the north, and various proposed solutions are being studied, including battery storage and re-injection into the local grid.

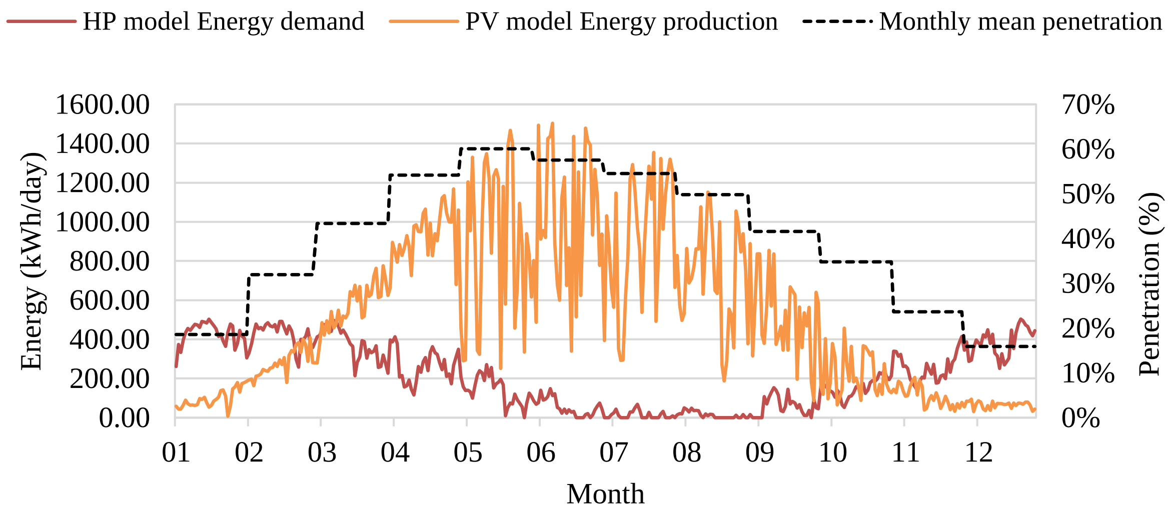

Figure 4.6. GCHP model's daily energy demand and PV panels model's daily energy production, alongside the monthly mean penetration.

Table 4.3. Annual and seasonal values for total solar energy production, GCHP energy requirements and mean penetration.

Time period	PV model production (MWh)	GCHP model demand (MWh)	Mean penetration (%)
Winter	13,121	37,175	22%
Early spring	73,648	23,673	52%
Spring	30,152	1,513	58%
Summer	65,993	2,725	45%
Fall	10,021	12,602	29%
Annual	**192,935**	**77,688**	**37%**

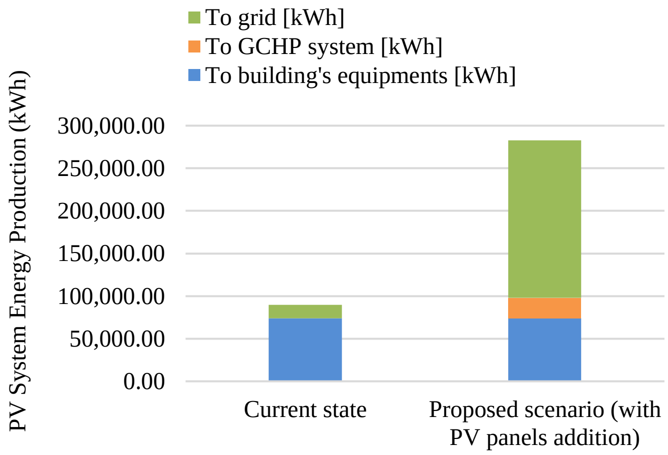

Figure 4.7. PV panels energy production distribution for current state (Case 1) and proposed SAGCHP system (Case 2).

4.4. GHG emission and cost analysis

Finally, we want to study the impact of such a new SAGCHP system, and compare the amount of emissions emitted, in tons of CO_2 equivalent (tCO_2eq), and have an estimation of the project's cost through NPC. At the building scale, the use of a SAGCHP reduces the annual heating load provided by the boiler by 268,200 kWh, but also increases the annual electricity demand of the building by 53,910 kWh as the solar energy does not meet the entire energy demand of the heat pump. Regarding heating and electricity consumption, results show that implementing a SAGCHP system reduces the GHG emissions by 38.3 tCO_2eq (6% decrease) each year and decreases the annual energy cost by 19,930 CA$ (3% decrease). When expanding the analysis to the community scale, the solar energy surplus exported to the grid benefits both environmentally and economically, increasing GHG emissions reductions to 176.7 tCO_2eq (28% decrease) and energy cost savings to 164,960 CA$. Using Quebec's 2021 carbon pricing of 22.6 CA$/ tCO_2eq (27% decrease), these additional emission reductions translate to a potential annual carbon cost savings increase from 866 CA$ at building scale to 1,804 CA$ at community scale, highlighting the environmental and economic benefits of grid integration.

Table 4.4. Summary of costs of the 25-year economic analysis, annual heating loads according to the energy source (boiler or geothermal), and GHG emissions for Case 1 and Case 2 scenarios.

	Case 1 **Current real-life state**	**Case 2** **Proposed SAGCHP scenario**
Capital cost (CA$)	19,980	3,319,370
Annual operational costs (CA$)		
Energy	630,060	610,130
Maintenance	3,650	4,700
Heat source (kWh)		
Oil boiler	595,690	327,490
GCHP	0	268,200
Electricity source (kWh)		
Local grid	456,892	615,309
PV panels	71,805	95,578
GHG emissions (tCO_2eq)	644	606

The financial analysis made over a 25-years period, considering the SAGCHP scenario (Case 2) with a drilling cost of 300 CA$/m and a PV system cost of 5 CA$/W, shows a NPC of -12,065 kCA$ which is higher than the NPC of -8,119 kCA$ for the current oil boiler and PV system (Case 1). This means that Case 2 scenario would be less economically viable. To go further, several combinations of PV and drilling costs and their impact on NPC were analysed, at both building and community scale. Figure 4.8 shows NPC evolution at building scale and demonstrate that, no matter the PV or drilling cost, the SAGCHP project does not achieve a competitive NPC compared with the current scenario. However, the project profitability is more interesting when considering the community scale (Figure 4.9a). Similar results are presented in Figure 4.9b, except that the metric used is the percentage of return on investment (ROI) that is achieved after the 25-year analysis. On both heatmap, the dashed lines mark the project's profitability boundary. Case 2's scenarios to the left of the line are more attractive than business as usual (Case 1) with a lower NPC and a positive percentage of ROI achieved. Case 2's scenarios to the right of the line are less attractive than business as usual, with a higher NPC and no ROI. With a drilling cost of 300 CA$/m, Case 2's NPC cannot be competitive with Case 1. If we consider reducing the PV cost to Quebec's average value of 3 CA$/W, the drilling cost should not exceed about 130 CA$/m to make the project attractive. The drilling cost appears to be to have the most influence on the capital cost, thus on the project viability.

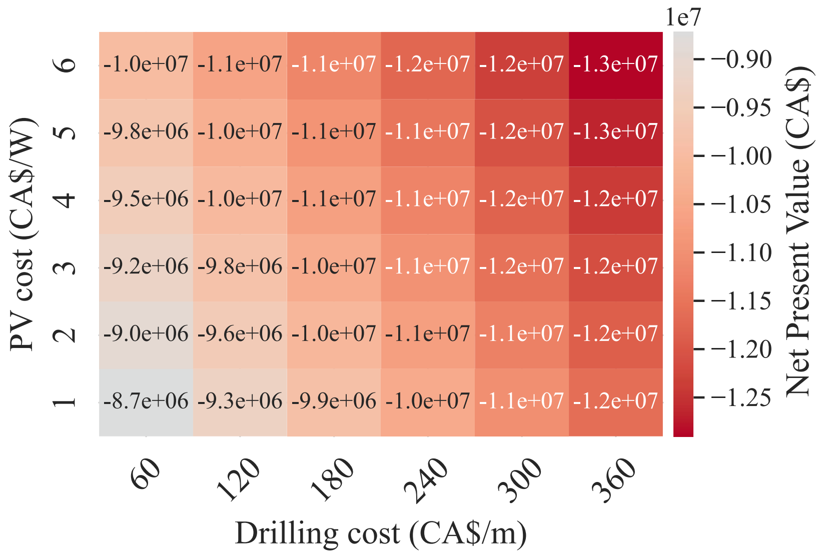

Figure 4.8. NPC values at building scale for different combinations of drilling and PV system costs.

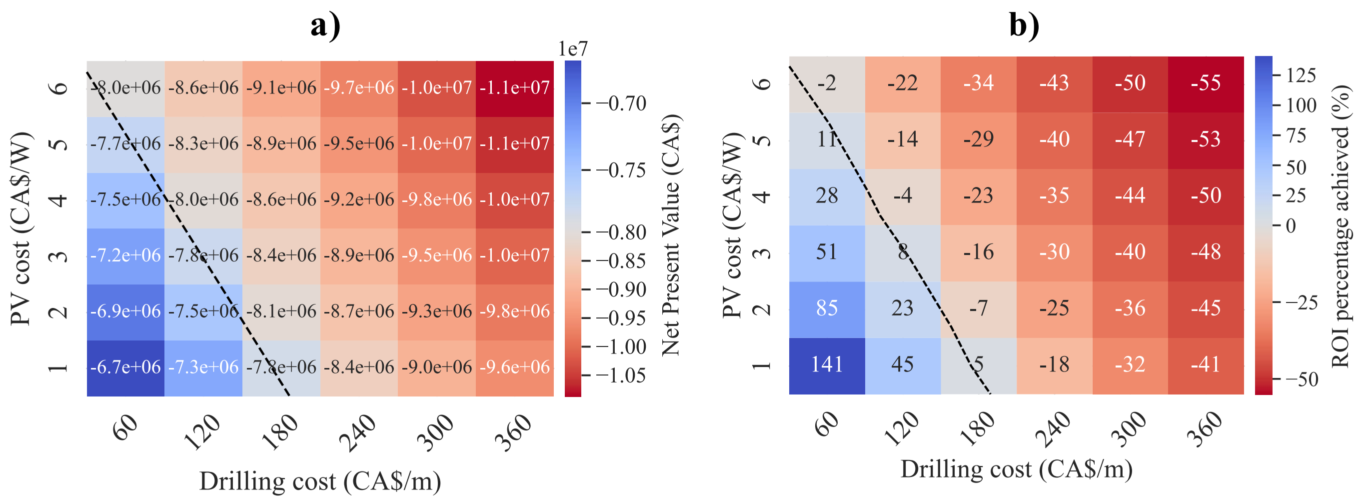

Figure 4.9. NPC values (a) and percentage of ROI achieved (b) at community scale for different combinations of drilling and PV systems costs.

However, the economical challenge of such a project in Northern Quebec is known and the financial metrics calculated here need to be put in perspective. Additional factors can strengthen the option in favour of a sustainable energy transition. First, the project aligns with growing policy support for clean energy initiatives in northern communities and could surely qualify for government incentives and grants that could significantly improve the financial viability. Second, as carbon prices fluctuates over time in Canada, a SAGCHP system enables the building to increase its energy self-sufficiency and to withstand future carbon tax increases. And most importantly in Nunavik context, the SAGCHP system as well as other sources of local renewable energy can enhance building's energy security by reducing dependence on oil deliveries and price increases. The environmental and social benefits, combined with potential for additional policy support, make it a worthwhile investment for the building's long-term sustainability and operational stability.

DISCUSSION

The implementation of SAGCHP system in northern remote communities present both promising opportunities and significant challenges that warrant careful consideration. This discussion examines the key findings of our study while considering limitations and future research directions.

Regarding the simulation methodology, some limitations should be considered when interpreting the results. The use of Meteonorm weather data from TRNSYS 18 documentation provides a standardize basis for analysis but may not fully capture the actual 2023-2024 climate conditions in Kuujjuaq. Also, the Arctic region is highly sensitive to climate change and Nunavik is expected to experience significant changes in weather conditions in the coming years [27], [50], [51]. Future studies would benefit from using real-year weather data or climate prediction models to enhance the reliability of the building's simulation results. Model's accuracy can also be influenced by uncertainties in building operation parameters, including occupation fluctuations, occupants' behavior, manual settings, ventilation flows, real heat consumption patterns, and other values that can deviate from theoretical assumptions. This gap between model's predictions and building's real energy use is known as energy gap and is the subject of numerous research projects aimed at reducing it [52], [53], [54].

Due to Nunavik's extreme climate conditions, the severe imbalance between ground heat extraction and injection periods is identified as a substantial challenge in implementing a GCHP system [15], [16]. This imbalance affects the long-term stability of ground temperatures and system performance. Seasonal thermal storage strategies emerge as a potential solution to address this thermal imbalance as well as the characteristic mismatch between energy demand and solar production in northern regions. One recommended solution for maintaining a balanced soil temperature could be to use the heat from the ambient air during the hottest periods of summer to inject it into the soil. That aspect has not been simulated in this study as we choose to analyze the viability of the system under the most demanding conditions, without heat reinjection. A robust GHE system was designed and assessed to provide operational temperatures above or close to the minimum allowed for conventional heat pumps throughout the system's lifetime. Previous research confirmed that ventilation heating and in-floor heat delivery are the most relevant way to use geothermal energy, as they can function with low temperatures around 30-50°C, unlike baseboard heat emitters that requires fluid temperatures of 60-80°C [6], [9]. For the solar PV system, the risk of snow accumulation on PV panels has not been considered, but it would be of great interest to add a loss coefficient in the simulation in future research, as done in [48].

The management of excess solar energy production presents other options:

- Utilizing excess production from the additional PV system for auxiliary building's electricity loads, and thereby reducing grid dependency.
- Adding battery storage systems for time-shifting solar energy use, especially during non-daylight hours. However, the associated costs of batteries remain an important consideration despite the ongoing improvements and price reductions of the technologies. At community scale, Moreno [17] showed that injecting surplus electricity into the grid is always more cost-effective than battery storage.

The most interesting solution, therefore, is to adopt a community-wide vision by exporting excess power back to the local grid, creating mutual beneficial arrangements between building owners, local grid operators and community users. While biomass represents one of the most attractive techno-economic alternatives to diesel [55], communities remain dependent on imports, unlike geothermal energy which increases energy independence. Moreno [17] showed that an energy mix supply, like a combination of geothermal, photovoltaic and biomass systems, is the most interesting option to ensure reliability and carbon emission reduction. During 2024, in Fairbanks, the Alaska campus was running one third on their horizontal ground loop system, one third on a biomass boiler and the final third on a diesel boiler [7]. Other studies demonstrate that the rentability of a GSHP system significantly varies according to fuel oil prices [8], [56]: when oil costs are high, GSHP systems allow for more savings compared to a conventional oil boiler. Hence, an optimal solution can be found using thoughtful energy mix to reduce significantly GHG emissions: solar and geothermal energy to benefit from local renewable energy and increase sovereignty, and biomass energy to support and fill the gaps left by the first two. This study aims to fill the gap in arctic and subarctic building's energy consumption, solar PV system production and investigation for shallow geothermal heat pump systems. Deep geothermal systems were not discussed here but are also promising solutions for sustainable energy in the North, and several pilot projects are underway in Canada [57], [58].

Over the past decades, melting sea ice in the Canadian Arctic and development of Northern communities has led to an increase of fuel consumption and shipping, and the risk of oil spills has multiplied. Whether they occur offshore or on land, these oil spills have catastrophic consequences for ecosystems, societies and the economy, and they are recognized as serious issues by governments of USA, Canada and Russia [59], [60], [61], [62]. Reducing oil consumption in communities by developing local and renewable energy sources is the first step to tackle this problem.

The results of this study can be applied to any other regions presenting similar climate conditions. Data on building's heat loads are useful for areas presenting similar temperature normal (-5.4 °C [26]), HDD18 (8,523 [27]); data on PV panels production can be applied for communities located around the same latitudes (58°); while results on GCHP design would be mostly appropriate in sporadic and discontinuous permafrost areas like Kuujjuaq [63]. This is the case of other subarctic regions found in Canada and within the Yukon and Northwest Territories. Conclusions on GCHP performance might not be relevant for regions facing more severe arctic climate and continuous permafrost, like in Nunavut (Canada) for example. The type of heat and power distribution network is also important. Results and conclusions of this study will be useful for remote communities that rely on integrated and local energy system, like in Canada, Alaska, Greenland, and part of Russia. Scandinavian countries, Iceland, and some areas in Russia are typically connected to a national grid, hence, the strategies for decarbonization might be different.

Eventually, as mentioned earlier, the economic viability of SAGCHP system in remote northern communities must be evaluated within the context of rising energy costs, carbon pricing policy, and environmental benefits, social benefits of local energy production and increased energy independence.

CONCLUSION AND RECOMMENDATIONS

This study addresses an important knowledge gap regarding building energy consumption and renewable energy integration in Nunavik and Northern Canada. Our report focuses on analyzing the heating demand of the Kuujjuaq's Forum (Nunavik, Québec). A building model was developed using TRNSYS 18 software to investigate and quantify the heating demand profiles, with a particular emphasis on ventilation requirements. These profiles were used as input values to size a ground-source heat pump system with Versa GLD software. Then, a dynamic model of the vertical geothermal heat exchanger was built in TRNSYS 18 and coupled with heat pumps to supply air preheating loads. Eventually, heat pumps energy demand was compared to the energy production of additional PV panels that would cover the entire roof of the building. The findings demonstrate the potential of SAGCHP systems for the Kuujjuaq Forum, with several key outcomes:

- The Forum's real heating consumption averages 577 MWh/year, including radiators, ventilation and domestic hot water. Building model reaches similar results with an annual heat demand of 574 MWh, corresponding to an energy use of about 143 kWh/m². Ventilation heating accounts for 381 MWh of this load, with preheating (268 MWh) and terminal heating (113 MWh).
- Analysis confirms that GCHP could be a viable option to manage a significant portion of the ventilation heating load, particularly the air preheating which accounts for 70% of the total air heating demand and 47% of the total heat demand (ventilation, radiators and DHW). The system design indicates that a minimum of 60 boreholes with a borehole depth between 160 and 200 m, corresponding to 9,600 to 12,000 linear meters of heat exchangers, would be required to ensure reliable operation within the heat pump's operational parameters, considering the average ground temperature of 1.8°C.
- The proposed GCHP system demonstrates an average COP of 3.44 and shows a maximum capacity of 88.30 kW to meet the requirements. Of the 77,980 annual kilowatt-hours required by the heat pump to meet air preheating load, approximately 23,773 kWh could be supplied by an additional PV system of around 1380 m² and 270 kW. This system's annual penetration averages 37%. Seasonal analysis reveals average solar energy coverage of 22% during winter and a peak average penetration reaching 53% during early spring.
- Despite an important investment cost, the economic and environmental analysis suggests that the SAGCHP could enable 19,940 CA$ and 38 tCO_2eq savings per year at building scale. The yearly benefits go up to 177 tCO_2eq and 164,960 CA$ savings if the analysis is extended to the community scale, taking into account solar energy exports from the PV system to the grid.

Assumptions about the proposed additional panels on the total surface of the roof were made. However, the building may have structural constraints that prevent the installation of more panels. If this is the case, another surface should be considered (for example the parking area) to increase the number of solar panels and therefore the system's capacity to power GCHP installation.

To conclude, this research provides unprecedented data and contributes to the understanding of heating and electricity consumption patterns in subarctic non-residential buildings, while also providing valuable insight on integrated PV systems performance. The results indicate that SAGCHP system can be technically viable for large-scale applications in Nunavik, like the Kuujjuaq Forum, but drilling and PV costs need to be competitive to ensure economic viability. While the economic challenges of implementing SAGCHP systems in Northern Quebec are significant, the combination of several factors such as potential government incentives, protection against rising carbon prices, and enhanced energy security can make it a strategically investment for long-term sustainability and operational stability in Nunavik. Such projects can offer meaningful reductions in both GHG emissions, operational costs, and oil dependence. A forthcoming pilot project, involving the installation of a small-scale GHE connected to the Forum, will provide crucial empirical data to validate the present findings and inform decisions for a full-scale system implementation.

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Annexe 1

Data Availability: The original data of the Kuujjuaq Forum, the TRNSYS energy model files, and the results data that are presented in the study are openly available in Borealis database at https://doi.org/10.5683/SP3/GW4LSV.