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Daily and seasonal heat storage for greenhouse food production in Nunavik (Canadian Arctic)

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ABSTRACT

Energy and nutrition are two of the main challenges for autochthonous people in the Canadian arctic territories. In Nunavik (northern Québec), Inuit people live in remote off-grid communities and diesel is the main source of energy providing both heating and electricity. Owing to global changes, traditional food such as wild fish, animals and berries are becoming more and more difficult to get, and imported food carried by boat and air more expensive. To date, 62 % of the Inuit families suffer from food insecurity and the development of means of local food production are critical for their future. Few community greenhouse projects have been developed in the last 20 years in different Nunavik villages, but none of them has heating systems and the production is therefore limited to a growing season that last about 4 months each year. This research activity aims at evaluating the potential of renewable energy systems for greenhouse production in Kuujjuaq, the capital and most populated village in Nunavik. In 2016, the community greenhouse in town has been instrumented with temperature, humidity and solar radiation sensors. Monitoring data have shown a significant day/night temperature difference that prevents optimal plant growing. To partially reduce daily temperature changes, in the fall 2018 a bed of pebbles with known thermal properties has been placed underneath the plants' soil to provide a daily heat storage medium. A controlled air circulation system transfers heat to the pebbles during the day and backwards during night-time. The first results show that the system is reliable and can guarantee an efficiency of 3, with 40-50 kWh of solar heat that would otherwise be lost through air ventilation. Horizontal and vertical underground seasonal storage systems were additionally simulated to evaluate the possibility of extending the production season currently ending in September. Even though the ground hosting the horizontal system shows lower thermal properties than the deeper saturated sediments, the horizontal storage option can guarantee better performance in terms of available energy, with 13 MWh of energy transferred to the greenhouse from October to December and 57 % of heat recovery. Nevertheless, the system should be better optimized in order to provide a higher and more stable temperature of the fluid circulating into the heating system. In conclusion, coupling daily and seasonal storage technologies can be an interesting and cost-effective option to provide renewable heat to northern greenhouses in order to both anticipate and extend the growing season by at least 2-3 weeks.

1. INTRODUCTION

Québec territory north of the 55th parallel is a vast region called Nunavik, populated by 14 Inuit communities with an approximate population of 12,300 people (SHQ, 2014), distributed along the coasts of a peninsula bounded by the Hudson Bay (W), Hudson Strait (N) and Ungava Bay (E). The regional capital, and biggest among the communities, is Kuujjuaq (58.10°N, -68.42°E), a village of 2375 inhabitants located 53 km upstream from the estuary outlet of the Koksoak River in the Ungava Bay. Electricity, space heating (SH) and domestic hot water (DHW) production in all these villages are provided by diesel power plants and furnaces. The cost of electricity production by diesel generators operated by Hydro-Québec, the provincial energy producer, is around 0.75 CAD$ kWh^{-1} (CAD = Canadian dollar) in Kuujjuaq (Hydro-Québec, 2011). As a comparison, the cost of hydro-power generation in the rest of Québec is 0.03 CAD$ kWh^{-1} on-grid and 0.40 CAD$ kWh^{-1} off-grid (Belzile et al., 2017a). In such Inuit villages, each house has its own diesel furnace providing SH and DHW. The arctic diesel price amounted to around 2.03 CAD$ l^{-1} in 2018 in Nunavik (Makivik, 2018). In addition to these high economic costs, the environmental impact amounts to thousands of tons of CO_2 emitted every year, contributing to air pollution and climate warming in an arctic environment already subject to permafrost degradation, with effects on both ecosystems and society (Allard and Lemay, 2012).

To this regard, the study of possible alternatives is of utmost importance to reduce the costs and environmental impacts of energy production in these communities (e.g. Yan et al., 2019). Among the suitable renewable technologies, ground source heat pumps (GSHP), underground thermal energy storage systems and deep enhanced geothermal systems are under study to evaluate the potential contribution of geothermal energy to provide SH and DHW (Belzile et al., 2017b; Miranda et al., 2018; Giordano and Raymond, 2019; Gunawan et al., 2019). Besides the technical issues (e.g., strongly heating dominated buildings, permafrost conditions), drilling activity remains an expensive element of GSHP systems, especially in Nunavik, which has to be considered in the development of the technology. For example, Giordano et al. (2019) defined 150 CAD$ m^{-1} as a threshold cost of BHE drilling and installation in order to guarantee interesting payback times, while current drilling offer stands at more than 300 CAD$ m^{-1}, essentially due to lack of local expertise. A detailed 50-years life-cycle cost analysis by Gunawan et al. (2019) showed that, with public incentive programs, GSHP can be more economically attractive than the diesel base case.

Interest in greenhouse (GH) food production has been rising among the northern off-grid communities in the last 15-20 years, due to the benefits offered by the possibility of locally produce fruits and vegetables. Allen (2013), Avard (2015) and Lamalice et al. (2018) reported not only benefits to population's health (e.g., increase in vegetable consumption and food security), but also social (e.g., gardening activities for kids and adults, social identity) and economic advantages (e.g., fruit and vegetable sales to the local market, reduced transportation costs, jobs opportunity). An inventory of northern GH in North-America made by Piché et al. (2019b) showed that at least 12 greenhouse projects are present and that three different types can be distinguished among community, commercial and research purposes. All of them have less than 20 years and half were built after 2010. The cultivated surface ranges from 30 m^2 (Fort Albany First Nation, Ontario, Canada) to 800 m^2 (Inuvik, North-Western Territories, Canada). Other gardening projects were recently kicked-off in Kangiqsujuaq, where there is no greenhouse, but a first successful trial was performed with cold frames in the summer 2016 and some additional gardening structures were built in 2018 (Lamalice et al. 2018). In the Cree and Inuit community of Whapmagoostui-Kuujjuarapik on the Hudson Bay, close to the southern limit of Nunavik, there are also one research GH and one community GH, the latter with an active community project started in 2019. Depending on latitude and climate, the growing season generally lasts between 4 and 7 months due to the absence of heating and/or storage systems. However, Chena Springs (Alaska, US) and Moberly Lake (British Columbia, Canada) reported GHs operating all year round with heating systems.

In Kuujjuaq, one of the two GHs has been instrumented in 2016 with a monitoring system to evaluate its yearly energy budget and, in agreement with the community, design a storage system to optimize and extend the current growing season. The paper presents the first step of a study aimed at evaluating the possibility of coupling daily and seasonal energy storage to heat this GH. After the climatic and geological description of the study site, the short-term and the long-term storage systems are presented separately. Preliminary results of the experimental system providing daily storage and the simulations of additional underground components providing seasonal storage are described and discussed to evaluate the potential benefits in terms of extending the growing season.

2. CLIMATIC AND GEOLOGICAL SETTING

Kuujjuaq (58.10 N, -68.42 E) is the main Inuit village in Nunavik among the 14 autochthons communities placed along the coasts of the Ungava peninsula (Figure 1). Kuujjuaq shows a subarctic climate with average annual air temperature of -5.8 °C and 8520 heating degree days below 18 °C. Mean solar radiation from May to September is 4.5 kWh m^{-2} d^{-1} and mean temperature from October to April is -14 °C (1981-2010 Climate normals; Environment Canada, 2019). A temperature increasing trend has nevertheless been observed from 1990 to 2010 with mean annual temperature increasing from -7 to -3.5 °C (Fortier et al., 2011). The presence of discontinuous but widespread permafrost is reported in the region (Allard and Lemay, 2012) and strongly depends on the local geological conditions (Lemieux et al., 2016). Shallow ground temperature monitored for one year near the GH clearly shows the insulating effect of snow cover (Figure 2). To give an example of the energy needs, reference buildings simulated in Kuujjuaq (residential house; Gunawan et al., 2019) and Kangiqsualujjuaq (research station; Belzile et al., 2017b) displayed a total heating load of around 70 MWh y^{-1}, SH and DHW included.

The study area is located in the west part of the Southeastern Churchill geological province (Simard et al., 2013 and references therein). The quaternary sediments mainly consist of littoral and pre-littoral sediments alternating to intertidal deposits related to different cycles of transgression and regression of the Iberville Sea (Fortier et al., 2011). Glacial till deposits often cover bedrock outcrops and it is common to find them underlying the marine sediments. Alluvial coarse-grained materials are only found along the small streams of two valleys.

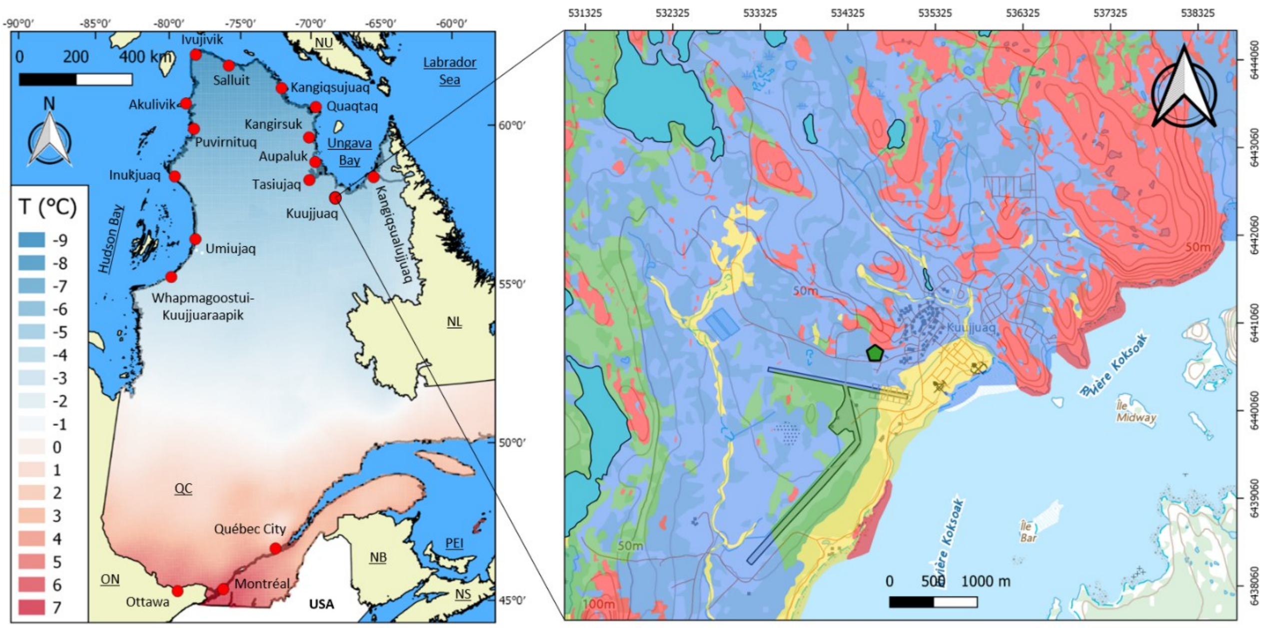

Figure 1: Geographical (left) and geological (right) setting in Kuujjuaq, with the near-surface undisturbed ground temperature and the distribution of the alluvial (yellow), marine (blue) and glacial (green) sediments and rock exposure (red). The greenhouse site is indicated by the green pentagon.

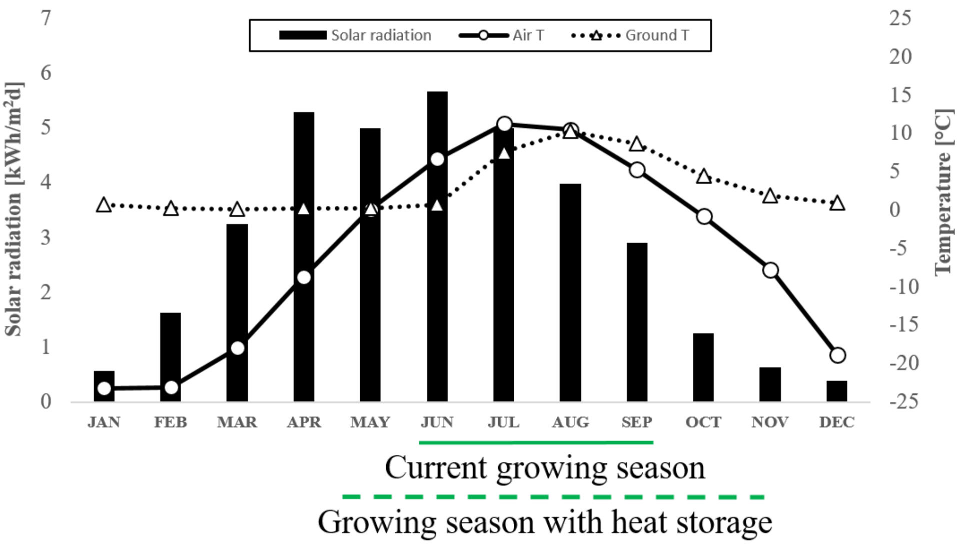

Figure 2: Climatic setting in Kuujjuaq (ground temperature was monitored at 0.25 m b.g.l. outside the greenhouse) and hypothesis on the duration of the growing season with both daily and seasonal heat storage.

3. METHODOLOGY

3.1 Greenhouse Description

Two greenhouses were built in Kuujjuaq, one in 1999 and one in 2012 (Figure 3a). Both of them are community greenhouses, i.e. each one is divided in small garden beds which are randomly distributed each year among the inhabitants. A crop monitoring was established in 2016 giving rise to an estimation of the harvest equals to 1.15 tons of fresh vegetable for the whole season. Green leafy vegetables (bok-choi, kales, kohlrabies, lettuces) represent 64 % of the total harvest. The remainder is composed of zucchinis, cucumbers, radishes, carrots, spinach and even few strawberries (Lamalice et al., 2018). These vegetables are cultivated in a soil imported from the south. The growing season in Kuujjuaq is about 4 months, from mid-May to end of September (Figure 2). Each greenhouse has a surface of 140 m^2 (18 x 8 m) and an envelope composed of double panels of polycarbonate. The oldest one shows a Quonset design, while the newest has a gothic-arch structure. None of them is heated, the only possible thermal regulation is carried out in summer by opening a part of the roof to avoid overheating (Figure 3b).

Figure 3: a) Kuujjuaq greenhouses, the one built in 2012 at the left, the one built in 1999 at the right. b) Greenhouse built in 2012 and its opening roof.

3.2 Daily Heat Storage System

The most recent greenhouse was instrumented in the summer 2016 and 2017 with several thermocouples and humidity sensor (Piché et al., 2019). Data analysis emphasizes the important difference between the day and night temperature during the growing season (Figure 4a). It can be observed that the day/night temperature difference is greater than 24 °C for more than half year. This means, for example, that if during the day the maximum temperature in the greenhouse was 30 °C, it decreased to 6 °C at night. This is harmful for plants whose optimal growth temperature is between 17 and 27 °C, i.e. 10 °C temperature difference between minimum and maximum values. About 25 % of the time, the difference reaches more than 30 °C. To counterbalance these situations, a daily heat storage system was built in the summer 2018 and kicked-off in the 2019 season. This thermal storage system includes three elements: a concrete slab at the centre of the greenhouse; gabions filled with rocks of 5 to 20 cm in size; and a pebble bed set up under the growing soil (Figure 4b). The concrete slab and the gabions are passive storage systems (to enhance the thermal mass within the greenhouse), while the pebble bed can be thermally charged and discharged through air streams, by means of fans and pipes. This active storage system contains about 41 tons of local rocks, mostly diorites, granites, and paragneisses. The heat capacity of these units has been analysed in the laboratory and show values of about 2.3 ± 0.1 MJ m^{-3} K^{-1} (Kanzari, 2019).

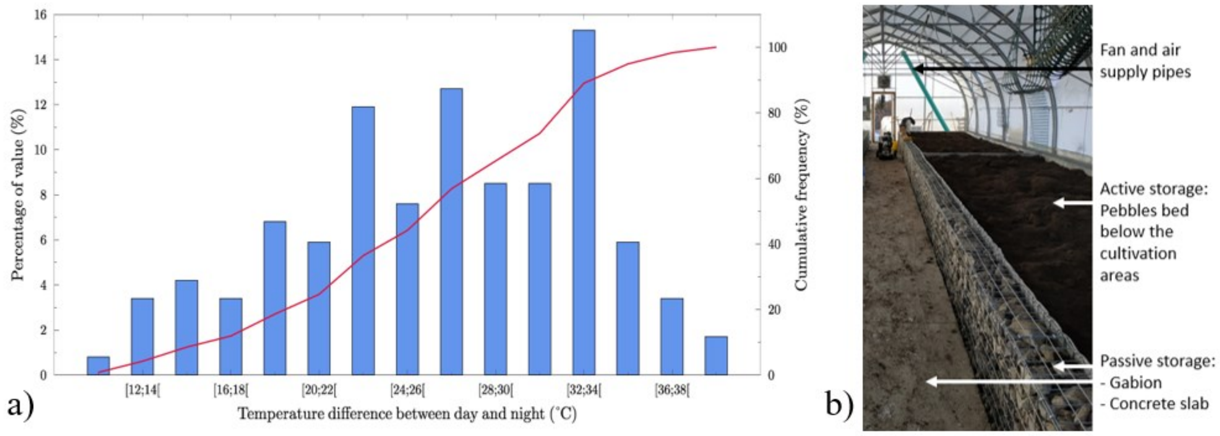

Figure 4: a) Day/night temperature difference during the 2016 growing season from June to September. b) Daily heat storage system installed in the greenhouse.

3.3 Seasonal Heat Storage System

A field campaign was carried out in Kuujjuaq in the summers of 2017 and 2018. Surveys involved rocks and quaternary sediments samples collection, temperature logs in wells, in situ hydraulic conductivity tests and electrical resistivity tomography (ERT) investigations. In particular, two ERT lines were carried out at the greenhouse site in order to investigate the shallow underground, identify the presence of permafrost, and thus evaluate the best option for the seasonal underground heat storage (Figure 5). Mixed Wenner-Schlumberger and Dipole-Dipole arrays were used to maximize lateral and vertical resolution of ERT profiles. Due to a highly resistive ground surface (compacted gravel), around 30 % of the resistance values were erased to increase the signal to noise ratio. The results show a very resistive first layer 2.5-3 m thick (2000-3000 Ω m), that is interpreted as compacted unsaturated gravels and sands. Below this, there is a conductive layer of marine sediments, supposedly saturated due to the low resistivity values (100-300 Ω m). Deeper in the section, two resistive zones can be described as permafrost mounds.

Two hypotheses of underground storage system were evaluated (Figure 5): 1) horizontal heat exchangers in the shallow underground, the first layer of compacted sands and gravels; and 2) vertical borehole heat exchangers (BHE) in the marine saturated sediments. The first has the following advantages with respect to the second option:

- A horizontal system is much cheaper because drilling activities can be avoided;
- As demonstrated by Giordano and Raymond (2019), a smaller subsurface volume can be more efficient and optimal for short discharge periods such as the case presented in this paper;
- As shown by ERT results, permafrost is likely to be present at the site under examination, and thawing can cause instability and affect the surrounding buildings' foundations.

The conceptual model for the horizontal system is therefore characterized by two layers of horizontal pipes buried into the partially saturated gravel and sand sediments, whose thermal properties were measured in the lab with a needle probe (Raymond et al., 2017). This unit has a thermal conductivity of 1.0 W m^{-1} K^{-1} and a heat capacity of 2.0 MJ m^{-3} K^{-1} (Giordano et al., 2017). Since both thermal properties are significantly lower than those of the deeper marine sediments unit, the spacing within the heat exchangers needs to be kept small in order to maximise the effectiveness of charging/discharging thermal energy.

The storage has rectangular dimensions of 18 x 22 m and a volume of around 1600 m^3. The solar and horizontal thermal energy storage (HTES) loops are coupled together through a cylindrical short-term storage tank (STST) and the heat carrier fluid consists of a mixture of water and 50 % vol. of propylene glycol (minimal working temperature -30 °C) to prevent freezing. The HTES loop is connected in parallel to the greenhouse heating loop, and they work alternatively from April to September (charge) and from October to December (discharge), respectively. During the charge phase, the solar thermal collectors produce energy that is transferred to the underground storage via the STST and the pipes distribute the heat from the centre to the outer zones of the storage volume. During the discharge, thermal energy is extracted from the HTES and transferred directly to the greenhouse heating system, simulated as radiant floor heating, with pipes buried in the plants' soil (Figure 6).

The above-described model was simulated with TRNSYS, a commercial simulation modular environment that allows the transient modelling of complex energy systems (Klein et al., 2017). Several different components (Types) are individually solved by single systems of equations and then coupled together to achieve the final outputs required by the user. The code has been widely adopted to simulate underground thermal energy storage systems in the last 20 years (e.g. Pahud, 2000; Diersch et al., 2011; Sibbitt et al., 2012; Terziotti et al., 2012; Flynn and Sirén, 2015; Rad and Fung, 2016). Different Types can be used to simulate horizontal pipes, such as floor slab with buried pipes (Type 993; e.g., Terziotti et al., 2012), stratified thermal storage model (Type 342; e.g., Sweet et al., 2012) and horizontal ground heat exchangers (Type 997), which was used in the current study.

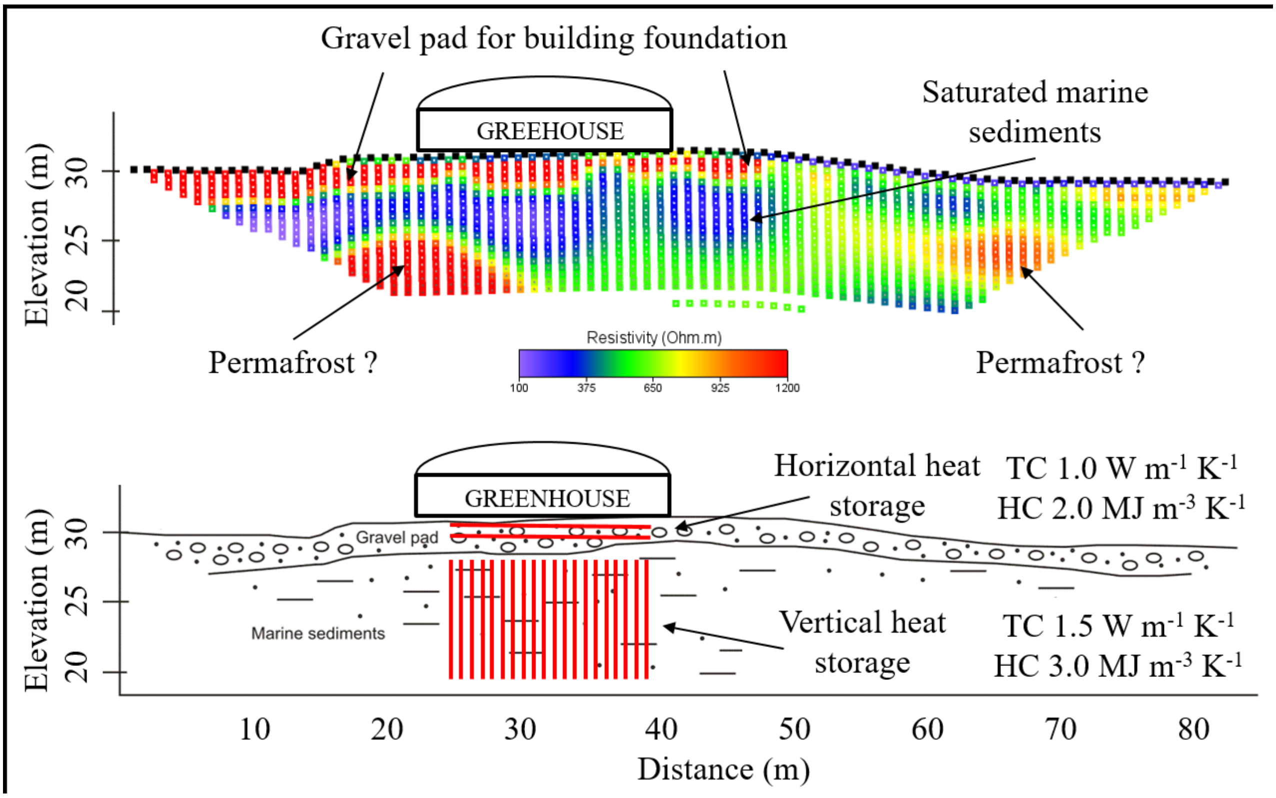

Figure 5: ERT results (upper) and geological interpretation (lower) below the greenhouse site. The two hypotheses of seasonal storage are also shown. TC, thermal conductivity; HC, heat capacity.

The entire HTES system was implemented in TRNSYS 18. The main Types used are:

- Type 997 to simulate the horizontal storage system. It was designed with two layers of twelve pipes horizontally spaced by 1.5 m at a depth of 1.5 and 3.0 m, divided in 4 series hydraulically connected in parallel. The internal and outer diameter of the pipes are d_i = 34 mm and d_o = 42 mm, respectively;

- Type 534 to simulate the STST, a vertical cylindrical storage tank giving the needed flexibility on the number of inlets and outlets (up to 10), and number of nodes (up to 20) to increase the model complexity and consider water stratification. A 2-m height tank with volume of 5 m^3 was chosen, two inlets and outlets were selected to connect the solar and HTES loops and 5 nodes were used to provide high accuracy to the simulation;

- Type 1b was chosen for the solar panels. It simulates a flat-plate solar thermal collector with quadratic efficiency, a_0 = 0.8, a_1 = 13 kJ h^{-1} m^{-2} K^{-1} and a_2 = 0.05 kJ h^{-1} m^{-2} K^{-2}. The total collector area is 100 m^2, divided in 10 series of 4 collectors and specific flow rate of around 50 l s^{-1} m^{-2};

- Type 993 as the radiant floor heating for the greenhouse. It was designed with one layer of 16 pipes horizontally spaced by 0.5 m, divided in 4 series hydraulically connected in parallel. The depth of the soil layer is 0.5 m and the internal and outer diameter of the pipes are d_i = 34 mm and d_o = 42 mm, respectively;

- Type 15 for the typical meteorological year from the Kuujjuaq airport weather station to provide crucial input weather data to the solar panels and the storage volume. However, the temperature shown in Figure 2 was applied on the top of the ground storage as was considered more reliable.

This system was finally compared to a conventional borehole thermal energy storage (BTES) with vertical BHEs. The latter has the same features and Types of the horizontal, with the only exception of Type 997 that was replaced by Type 557a, solved by the duct storage model developed by Hellström (1989). The cylindrical-shape vertical storage is made of 25 1-U BHE (well diameter of 75 mm, pipes with d_i = 21 mm and d_o = 26 mm) at 20 m depth, with a spacing of 2 m and a total volume of around 1700 m^3. The two systems have been simulated for an entire cycle of charge, from April (2160 h) to end of September (6552 h), and discharge, from October (6552 h) to December (8760 h).

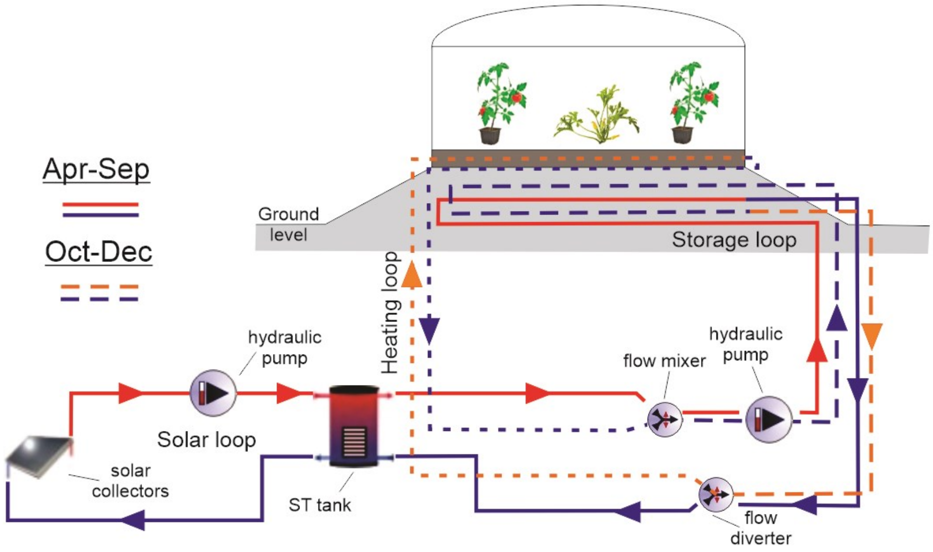

Figure 6: Horizontal seasonal storage concept for the greenhouse.

4. RESULTS

4.1 Daily Heat Storage System

The daily storage system was started in mid-May 2019. As its name suggests, passive storage is not supervised. In contrast, the operation of the active one is supervised via a climate controller made by Harnois Envirotrol. When the greenhouse inside temperature reaches 24 °C, the fan turns on and the system starts charging the pebbles until the temperature falls below 18 °C. The discharge begins when the temperature falls below 12 °C and stops when the temperature reaches 14 °C.

During the first period of operation, the energy analysis emphasizes that the desired effect has been achieved, with the temperature inside the greenhouse remaining well above the set temperature of 12 °C. The storage period is determined by the temperature level in the greenhouse with a threshold of 24 °C. The charging time is therefore directly dependent on the external weather and in particular on the solar resource. Two charge/discharge cycles have been compared and shown in Table 1: Charge 2 is shorter and stores less energy (E_{rock}) than Charge 1. This is related to the fact that the solar energy collected by the greenhouse (E_{sun}) during Charge 2 is lower than in 1. On the other hand, the two night-time discharges show similar results. The energy recovered by the air (E_{air}) in contact with the rock bed during the two discharges remains fairly close (42 vs. 49 kWh).

The efficiency of the system can be estimated by considering that the thermal energy recovered during the discharge was stored during the previous charging phase. Thus, the electricity consumption (E_{elec}) to be considered corresponds to the complete charge/discharge cycle. Under these assumptions, an efficiency of about 3 (E_{air} (Discharge 2) / E_{elec} (Charge 2 + Discharge 2) = 3) can be estimated over the charge/discharge cycle 2. More results and the operating details of the system can be found in Piche et al. (2019).

Other than reducing the air temperature fluctuation in the greenhouse, the system can also be useful to anticipate the start of greenhouse activity by 2-3 weeks with respect to the actual beginning. Indeed, the rock-bed placed underneath the plant's soil can easily help the frozen soil to thaw earlier due to the high solar production measured in April.

Table 1: Example of two charge/discharge cycles of the experimental daily storage system.

Phase	Duration	E_{air} [kWh]	E_{rock} [kWh]	E_{sun} [kWh]	E_{elec} [kWh]
Charge 1	9h05	-46.7	68.1	673.0	9.4
Discharge 1	6h30	42.4	-45.9	21.5	6.8
Charge 2	8h35	-28.2	20.4	485.0	8.9
Discharge 2	7h10	49.2	-59.4	34.9	7.5

4.2 Seasonal Heat Storage System

The TRNSYS simulations showed that the HTES can produce and transfer to the horizontal buried pipes an amount of 23.3 MWh of energy from April to September (solar efficiency 27 %). 13.3 MWh were then recovered during the discharge, giving a heat recovery (HR) of 57 %. The total energy loss amounted to 8.6 MWh, while the residual 1.2 MWh of heat remain stored in the ground volume. The average temperature of the storage raised to about 17 °C at the beginning of September, and fell down to 6 °C at the end of the simulation (December 31st; Figure 7). The BTES system produced 37.6 MWh (solar efficiency 44 %) and allowed recovering 8 MWh during the discharge, with a HR of 21 %. The total loss amounted to 22.5 MWh, 18.6 of which occurred on the side of the system, while 7.2 MWh of heat remain stored in the underground at the end of the simulation. The average temperature of the BTES followed a similar behavior of the HTES (Figure 7).

Simulated fluid temperature indicates that the HTES performs better than the BTES in terms of storage. The solar efficiency is higher in the vertical system because the temperature in the water tank remains lower due to a continuous exchange with the cooler underground. However, the BTES system loses more energy due to its wider lateral surface, and only 8 MWh are recovered during the discharge, compared to 13 MWh for the HTES. On the other hand, the BTES is more efficient in terms of temperature of the heating system; it can provide a heating fluid at 13 °C (in Figure 7) at the beginning of October (6552 h), falling to 7 °C at the beginning of November (7296 h) and to 5 °C at the end of December (8760 h). The HTES can provide 13 °C at the beginning of October, but then drops down to below 10 °C few hours later.

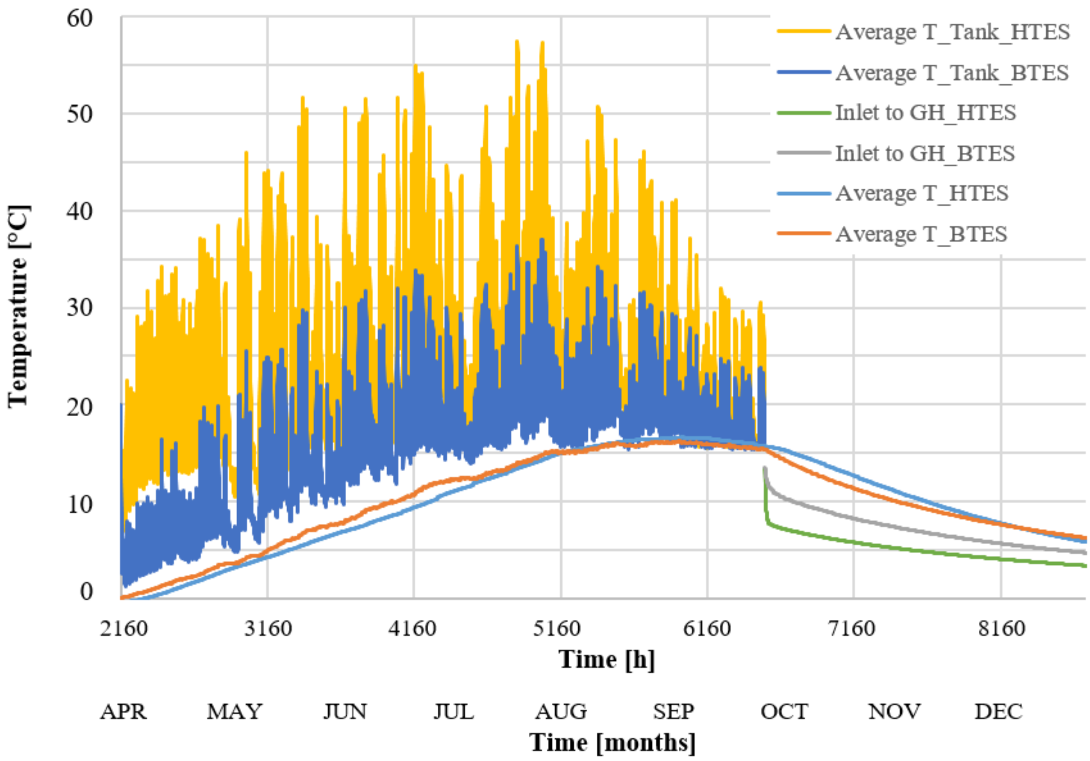

Figure 7: Simulated fluid temperature in both the horizontal (HTES) and vertical (BTES) systems.

5. DISCUSSIONS AND CONCLUSIONS

Preliminary results of a study aiming at evaluating the efficiency of both daily and seasonal heat storage to extend the growing season of a community greenhouse located in Kuujjuaq, Nunavik, were presented. The greenhouse is currently not heated and the growing season goes from mid-May to the end of September. An experimental rock-bed system was put in place to reduce the day/night air temperature difference and attain the optimal temperature for plant's growing. The first results show that the system is reliable and can guarantee an efficiency of 3, with 40-50 kWh of heat provided to the ambient air during the night (daily discharge). This system takes advantage of the solar heat that is daily trapped in the greenhouse and would be otherwise lost through air ventilation. However, the daily storage is expected to lose effectiveness over the summer period since the solar radiation drops from about 6 kWh m^{-2} d^{-1} in June to about 3 kWh m^{-2} d^{-1} in September and it would not be able to provide the same amount of energy during night-time in the fall. A seasonal storage is therefore crucial to extend the growing season and take advantage of the summer solar radiation. Two different systems were proposed and simulated to evaluate their effectiveness in terms of heat recovery and temperature of the heating system. The horizontal system (HTES) has several advantages with respect to the vertical one (BTES) because it does not require drilling and does not interact with the possible local permafrost. Even if the thermal properties of the geological materials hosting the HTES are weaker than the deeper saturated sediments hosting the BTES, the HTES performs better in terms of available energy (13 vs. 8 MWh of heating supplied) and heat recovery (57 vs. 21 %), whereas the system should be better optimized in order to provide a higher and more stable temperature of the fluid circulating into the heating system. The horizontal storage can therefore be a viable, reliable and cost-effective option to provide renewable heat to the greenhouse and extend the growing season by at least 2-3 weeks, to mid/end of October.

Future activities will focus on the optimization of the horizontal system and the coupling of the daily and seasonal storage here presented, with simulations of both systems. An optimal control on both short and long-term storage will be crucial to take the best out of each technology and provide the optimal growing temperature for the longest period.

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REFERENCES

Allard, M., and Lemay, M.: *Nunavik and Nunatsiavut: from science to policy: an integrated regional impact study (IRIS) of climate change and modernization*, ArcticNet, Quebec City, (2012), 303 p.

Allen, T.: Costs and benefits of a northern greenhouse, *Proceedings*, 8th Circumpolar Agricultural Conference & Inaugural University of the Arctic Food Summit, Alaska Agricultural & Forestry Experiment Station, Girwood, Alaska, (2013), 58–63.

Avard, E.: *Northern greenhouses: an alternative local food provisioning strategy for Nunavik*, PhD Thesis, Université Laval, Québec City, (2015).

Belzile, P., Comeau, F-A., Raymond, J., and Lamarche, L.: *Revue technologique: efficacité énergétique et énergies renouvelables au nord du Québec*, INRS, Centre Eau Terre Environnement, Québec City , Research Report R1716, (2017a), 37 p.

Belzile, P., Comeau, F-A., Raymond, J., Lamarche, L., Carreau, M.: Arctic climate horizontal ground-coupled heat pump, *Transactions*, Geothermal Resource Council, **41**, (2017b), 22 p.

Flynn, C., and Sirén, K.: Influence of location and design on the performance of a solar district heating system equipped with borehole seasonal storage, *Renewable Energy*, **81**, (2015), 377-388.

Fortier, R., Allard, M., Lemieux, J-M., Therrien, R., Molson, J., and Fortier, D.: *Cartographie des dépôts quaternaires des villages nordiques de Whapmagoostui-Kuujjuarapik, Umiujaq, Salluit et Kuujjuaq*, Rapport de synthèse de la phase I, Ministère du Développement Durable, de l'Environnement et des Parcs du Québec, GM 65971, Québec City, (2011), 122 p.

Giordano, N., Kanzari, I., Miranda, M.M., Dezayes, C., and Raymond, J.: Shallow geothermal resource assessments for the northern community of Kuujjuaq, Québec, Canada. *Proceedings*, IGCP636 Annual Meeting, Santiago de Chile, (2017), 3 p.

Giordano, N., and Raymond, J.: Alternative and sustainable heat production for drinking water needs in Nunavik (Canada): borehole thermal energy storage to reduce fossil fuel dependency in off-grid communities, *Applied Energy*, **252**, (2019), 113463.

Giordano, N., Riggi, L., Della Valentina, S., Casasso, A., Mandrone, G., and Raymond, J.: Efficiency evaluation of borehole heat exchangers in Nunavik, Québec, Canada, *Proceedings*, 25^{th} IIR International Congress of Refrigeration, Montréal, (2019), 8 p., doi 10.18462/iir.icr.2019.547.

Environment Canada, http://climate.weather.gc.ca/climate_normals/index_e.html (accessed on May 2019).

Gunawan, E., Giordano, N., Jensson, P., Newson, J., Raymond, J.: Alternative heating systems for northern remote communities: Techno-economic analysis of ground-source heat pumps in Kuujjuaq, Nunavik, Canada, *Renewable Energy*, (2019), submitted.

Hellström, G.: *Duct ground heat storage model, manual for computer code*, Swedish Council for Building Research (BFR) and National Energy Administration, Lund, (1989), 49 p.

Hydro-Québec: *Réseaux autonomes, portrait d'ensemble et perspectives d'avenir*, Demande R-3776, HQD-13, Québec City, (2011), 35 pp.

Kanzari, I. : *Évaluation du potentiel des pompes à chaleur géothermique pour la communauté nordique de Kuujjuaq*, Master Thesis, Institut national de la recherche scientifique, Québec City, (2019), 99 p.

Klein, S.A., Beckman, W.A., Mitchell, J.W., et al.: *TRNSYS 18: A Transient System Simulation Program*, Solar Energy Laboratory, University of Wisconsin, Madison, (2017).

Lamalice, A., Haillot, D., Lamontagne, M.-A., Herrmann, T.M., Gibout, S., Blangy, S., Martin, J.-L., Coxam, V., Arsenault, J., Munro, L., Courchesne, F.: Building food security in the Canadian Arctic through the development of sustainable community greenhouses and gardening. *Écoscience*, **25**, (2018), 325-341.

Lemieux, J-M., Fortier, R., Talbot-Poulin, M-C., Molson, J., Therrien, R., Ouellet, M., Banville, D., Cochand, M., and Murray, R.: Groundwater occurrence in cold environments: examples from Nunavik, Canada. *Hydrogeology Journal*, **24**, (2016), 1497-1513.

Makivik Corporation: *Rise in the cost of gasoline*, Press release, Kuujjuaq, (2018), https://www.makivik.org/rise-in-the-cost-of-gasoline/.

Miranda, M.M., Dezayes, C., Giordano, N., Kanzari, I., Raymond, J., and Carvalho, J.: Fracture network characterization as input for geothermal energy research: preliminary data from Kuujjuaq, Northern Québec, Canada, *Proceedings*, 43^{rd} Workshop on Geothermal Reservoir Engineering, SGP-TR-213, Standford, (2018), 12 p.

Pahud, D.: Central solar heating plants with seasonal duct storage and short-term water storage: design guidelines obtained by dynamic system simulations, *Solar Energy*, **69**, (2000), 495–509.

Piché, P., Haillot, D., Gibout, S., Arrabie, C., Bédécarrats, J-P.: Thermal storage system devoted to greenhouse based in northern climate, Solar Energy, (2019a), submitted.

Piché, P., Haillot, D., Gibout, S., Arrrabie, C., Lamalice, A., Rousse, D.R., Py, X., Giordano, N., Raymond, J.: Serriculture circumpolaire : état de l'art et étude de cas au Nunavik, *Proceedings*, Colloque international Franco-Québecois en énergie, Baie St-Paul, (2019b), 6 p.

Rad, F.M., and Fung, A.S.: Solar community heating and cooling system with borehole thermal energy storage – Review of systems, *Renewable and Sustainable Energy Reviews*, **60**, (2016), 1550-1561.

Raymond, J., Comeau, F-A., Malo, M., Blessent, D., and López Sánchez, I.J.: The geothermal open laboratory: a free space to measure thermal and hydraulic properties of geological materials, *Proceedings*, IGCP636 Annual Meeting, Santiago de Chile, (2017), 3 p.

Société d'habitation du Québec: *Le logement au Nunavik - Document d'information*, Gouvernement du Québec, Québec City, (2014), 40 p.

Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J., and Kokko, J.: The performance of a high solar fraction seasonal storage district heating system – five years of operation. *Energy Procedia*, **30**, (2012), 856-865.

Simard, M., Lafrance, I., Hammouche, H., and Legouix, C.: *Géologie de la région de Kuujjuaq et de la baie d'Ungava (SRNC 24J, 24K)*, Gouvernement du Québec, Québec, (2013), 62 p.

Sweet, M.L., and McLeskey Jr., J.T.: Numerical simulation of underground seasonal solar thermal energy storage (SSTES) for a single family dwelling using TRNSYS, *Solar Energy*, **86**, (2012), 289-300.

Terziotti, L.T., Sweet, M.L., and McLeskey Jr., J.T.: Modeling seasonal solar thermal energy storage in a large urban residential building using TRNSYS 16, *Energy and Buildings*, **45**, (2012), 28-31.

Yan, C., Rousse, D., Glaus, M.: Multi-criteria decision analysis ranking alternative heating systems for remote communities in Nunavik, *Journal of Cleaner Production*, **208**, (2019), 1488-1497.