Sizing Horizontal Geothermal Heat Exchangers for Community Greenhouses in Montreal

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ABSTRACT

Community greenhouses are important for the production of local food and reduction of food supply insecurities within cities. As we've seen with Covid-19, pandemics highlight the criticality of local food access to underprivileged urban districts. Since almost 60 % of the energy used in greenhouses is spent in heating and cooling, ground heat exchangers (GHEs) can play a significant role in supplying temperature regulation, but geothermal heat pump systems tend to be expensive for community organizations. An efficient way to reduce GHEs installation costs is to dig trenches to install the system horizontally and cover a part of heating and cooling loads only. In order to ensure cost effectiveness and optimize operations, this type of system was studied for urban greenhouses where ground space can be limited. Sizing calculations were performed for GHEs of a 7.62 m x 15.24 m greenhouse located on the Island of Montreal where the annual, monthly, and hourly energy consumption were estimated from previous building simulations. Three scenarios were used to specify sizing of the system in terms of excavation dimensions and percentage of the greenhouse peak loads covered; (1) number and length of trenches required for a horizontal GHE (HGHE) covering 100% of cooling and heating loads; (2) number and length of trenches required for an HGHE to cover 100% of peak heating loads and 60% of peak cooling loads and; (3) the percentage of heating and cooling peak loads that can be covered by an HGHE located under the greenhouse with similar dimensions (around 116 m^2). Estimated excavation dimensions for cases 1 and 2 are 51.8 m x 8 m (414.4 m^2) and 40.8 m x 8 m (326.4 m^2). Estimated percentage of peak loads covered for case 3 is 40% of heating peak loads and 30% of cooling peak loads.

1. Introduction

Environmentally controlled agriculture such as greenhouses is becoming more and more popular due to its high output, which is 10 – 20 times greater per unit area than outdoor production (Ahamed et al., 2018). However, high energy costs are associated with greenhouses since temperature must always be controlled throughout the year. In greenhouses, temperature must stay higher than 10-12 °C and lower than 30-38 °C to avoid causing physiological damage to plants. Furthermore, temperature must not vary by more than 5-7 °C throughout the year (Mohamed, 2003). Thus, between 65 % and 80 % of the energy consumed by greenhouses is spent in heating and cooling, while the rest is spent in electricity and transportation (Zhang, 2020). Reducing heating costs is a big challenge for greenhouses growers, especially when located in colder regions.

It is widely known that climate changes and global warming are due to greenhouse gases, mostly of anthropogenic nature. Therefore, reduction of CO_2 emissions is becoming one of the main needs and worries (IPCC, 2014). Hence, transition toward sustainable energies is of great importance to succeed in decarbonization of the energy sector.

Ground source heat pump systems (GSHP) are the most popular option among geothermal direct use applications, with 71.6% of the installed capacity and 59.2% of the annual energy use reported in 2020 (Lund et al., 2020). Such systems however imply important installation costs when compared to conventional heating and cooling systems (Farabi-Asl et al., 2018). Slinky-coil horizontal ground heat exchangers (HGHEs) are cost-effective method for reducing installation costs of GHSP systems since this method requires a backhoe loader for shallow excavations instead of a drill rig for boreholes. However, this type of HGHE requires a decent amount of space to bury the heat exchange pipes, which makes it harder to apply in locations with limited space. In this case, the geothermal system can be coupled with another type of heating system or the heat exchange rate per unit of land area can be improved by optimizing the system design (Fujii et al., 2012; Fujii et al., 2013).

The objective of this project is to assess the potential of HGHEs in heating and cooling urban greenhouses and explore the alternative of installing this system under the greenhouse to save space, while considering a cost-effective method. Therefore, sizing calculations were realized considering an energy consumption profile for a greenhouse located in Montreal, using soil's thermal properties measured from samples taken on the Island of Montreal. Work was conducted in the scope of a multidisciplinary study where we aimed at providing affordable green technologies for community organizations operating greenhouses with simple means. Efforts was thus made to minimize HGHE length.

2. Materials and methods

2.1 Geology of Montreal

According to the *Système d'information géominière du Québec* (SIGEOM), except for some bedrock outcrops, most of the Island of Montreal is covered by sediments. During Quaternary, cold periods favored the growth of continental glaciers over North America. Hence, the Laurentidian inlandsis covered eastern Canada and part of the U.S.A. The island is mostly covered by undifferentiated till deposits belonging to Fort Covington and Malone Glacial Episodes, offshore deep-water sediments (clay, silt, locally calcareous) belonging to the Early St.

Lawence River Episode, undifferentiated alluvium belonging to the Malone Glacial Episode, anthropogenic sediments, organic sediments and nearshore shallow-water sediments (sand, gravel) belonging to the Champlain Sea Episode (Prest et al., 1982; Nadeau, 2019; Lepage, 1996). Sediment thickness varies from a few meters to more than 25 meters. The east coast generally shows more important thickness than the rest of the island (Lepage, 1996). Since the project implies a horizontal GHE instead of a vertical GHE, surface geology has more impact on the system than bedrock geology. The water table average depth relatively to the ground is 4.2 m but this varies with the location (Savard et al., 2013). Sediments found on the island of Montreal are shown in Figure 1.

2.2 Soil's thermal properties

In order to achieve sizing calculations, soil's thermal properties must be evaluated on the various studied sites. To do so, soil sampling was done on the site appearing on Figure 1; Grand Potager (45.55547, -73.6485). The fieldwork was done during June 2021. A manual auger was used to take undisturbed soil samples at a depth of 1 m. In total, 4 samples were taken in either an 18 g plastic cylinder with a volume of 115 cm^3 or a 438 g copper cylinder with a volume of 374 cm^3. Care was taken for samples taken on the sites to represent in situ conditions.

Once the sampling phase was completed, the sample analysis was conducted at *Institut national de la recherche scientifique* laboratories using a K2DPro – Decagon device with both the SH-1 and the TR-1 needles. SH-1 dual-needle with 3 cm length is to evaluate thermal conductivity (0.02 to 2.00 ± 10% W m^{-1} K^{-1}), thermal diffusivity (0.1 to 1.0 ± 10% mm^2 s^{-1}) and volumetric heat capacity (0.5 to 4.0 ± 10% mJ m^{-3} K^{-1}). TR-1 needle with 10 cm length is to evaluate thermal conductivity (0.1 to 4.0 ± 10% W m^{-1} K^{-1}; Decagon Devices, 2022). Every sample was analyzed in in situ and saturated conditions. Samples thermal properties measured was assumed to be the same on their respective site, which will enable sizing calculations to be done for the site. In situ thermal properties were used for the sizing calculations. Every sample was analyzed 4 or 5 times. A standard was used to correct the measured value before and after every test.

2.3 Sizing calculations

Two HGHE models are available for sizing calculations in GLHEPro V5.0; the straight horizontal and the slinky configuration. Both models are based on a finite line-source model with the uniform heat flux assumption. In this case, the slinky GHE model is chosen and uses a ring source model (Xiong et al., 2015). The increment in temperature $\Delta T(d,t)$ felt in the ground at time t (s) and distance d (m) from the borehole center is determined according to Marcotte and Pasquier's work (2009). The quasi-steady state heat transfer rate in terms of fluid transport is given by

$$2\pi R N_{\mathrm{ring}} q_{\mathrm{ln}} = \dot{m} c_{\mathrm{p}} [T_{\mathrm{in}}(t_{\mathrm{n}}) - T_{\mathrm{out}}(t_{\mathrm{n}})] \tag{1}$$

where R is the ring's radius (m), N_{ring} is the number of rings, q_{ln} is the heat transfer rate per trench length (W m^{-1}), $\dot{m}$ is the mass flow rate (kg s^{-1}), c_p is the specific heat (J kg^{-1} K^{-1}), T_{in} is the inlet temperature (˚C), T_{out} is the outlet temperature (˚C) and t_n is the time (s).

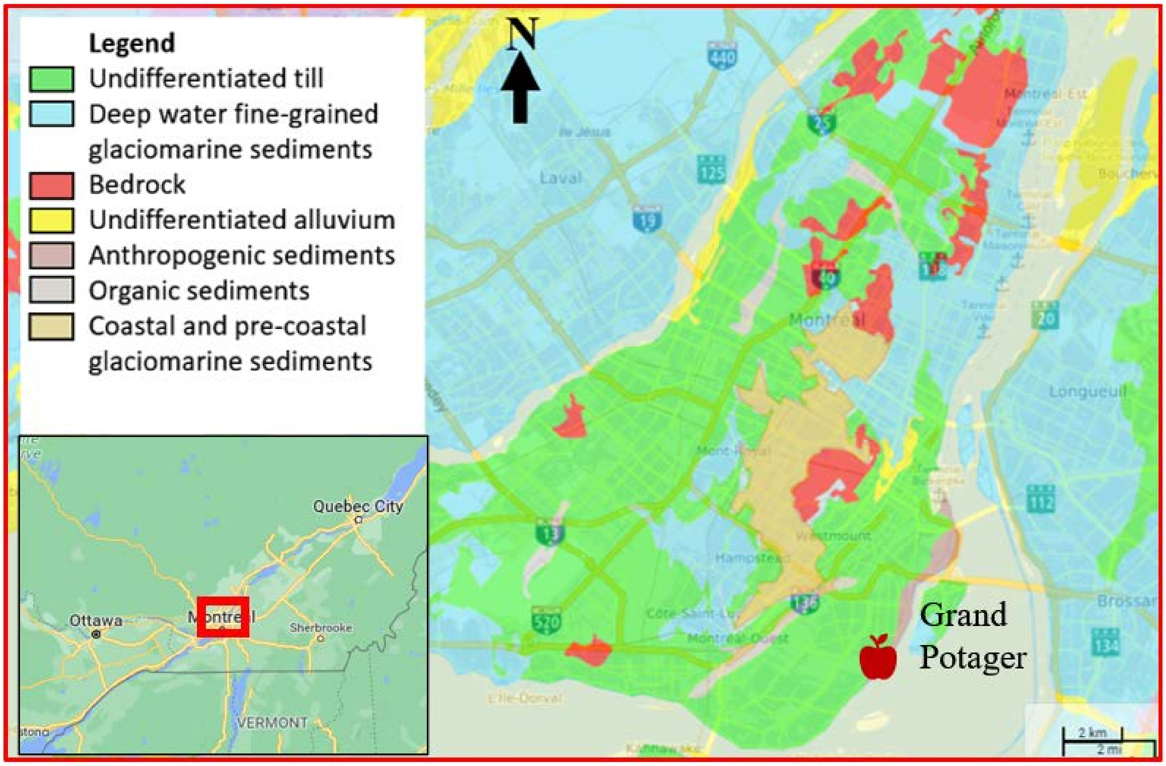

Figure 1. Location of Grand Potager greenhouse

Undisturbed ground temperature is determined with a temperature profile taken from 1971 to 2000 at Mirabel airport, at a depth of 1.5 m beneath the surface of the ground (Government of Canada, 2021), giving a minimum temperature of 2.1 ˚C during April and a maximum temperature of 12.8 ˚C during September. The maximum and minimum ground temperature are applied to be as conservative as possible and represent the lowest possible heat exchange during heating and cooling periods. An energy consumption profile for a greenhouse located in Montreal was used for the cooling and heating loads. The greenhouse was modelled in TRNSYS and calibrated using its monthly gas consumption and measured indoor air temperature and relative humidity. The software EnergyPlus with the user interface OpenStudio V2.2 were used to develop the building model (Léveillé-Guillemette et al, 2018; Lalonde et al, 2021). The profile is shown in Figure 2. The greenhouse's dimensions are 7.62 m X 15.24 m with a height of 3.66 m, orientated East-West. The structure is anchored in a concrete footing, but its floor (membrane) rests on crushed stone. No slab or insulation is present. The east and west walls are made of rigid polycarbonate while the rest of the envelope is made of air-blown double-walled polyethylene (Léveillé-Guillemette et al., 2018).

To fit the greenhouse's width, the calculations are made using 10 trenches. All inputs are shown in Table 1 and Table 2.

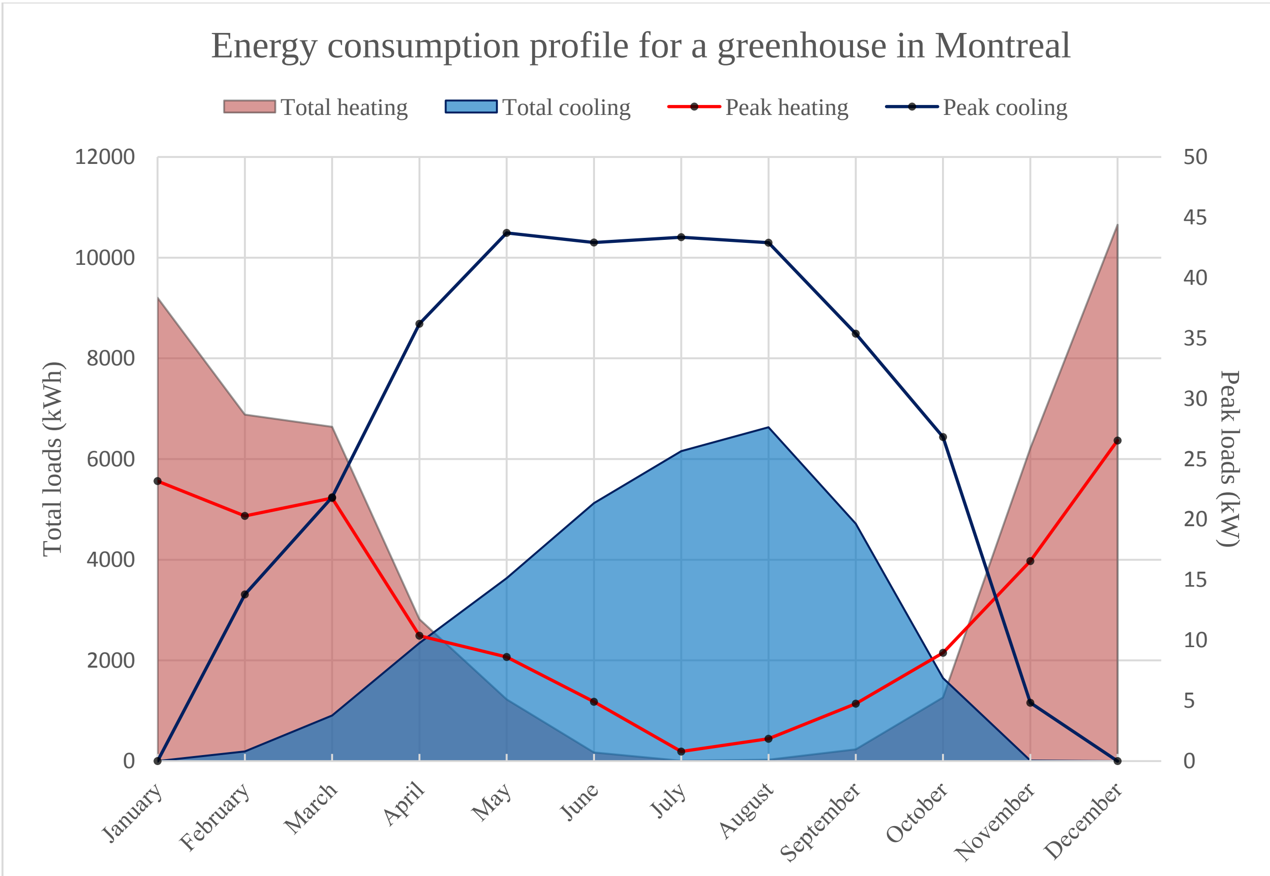

Figure 2. Energy consumption profile for a greenhouse in Montreal

Table 1. Sizing calculations inputs

Sizing calculations inputs	
Space between trenches (m)	0
Ring diameter (m)	0.8
Pitch (m)	1
Inner pipe diameter (mm)	44.2
Outer pipe diameter (mm)	50.0
Pump	ClimateMaster TCHV160
	Heating / Cooling
Ground temperature, Mirabel, 1.5 m depth (˚C)	2.1 / 12.8
Entering fluid temperature (˚C)	-8.9 / 29.8
Average fluid temperature (˚C)	-10 / 31

Table 2. Components thermal properties

Fluid, soil, and pipe thermal properties	
Average soil thermal conductivity (W m^{-1} K^{-1})	1.20
Average soil heat capacity (kJ K^{-1} m^{-3})	2269
Average pipe thermal conductivity (W m^{-1} K^{-1})	0.4
Average pipe heat capacity (kJ K^{-1} m^{-3})	1542
Propylene glycol/water concentration (%)	30
Freezing point of fluid (˚C)	-13.32

The calculations imply **three scenarios** in order to specify sizing of the system in terms of excavation dimensions and percentage of the greenhouse peak loads covered; **(1)** number and length of trenches required for an HGHE covering the entirety of the heating and cooling loads; **(2)** number and length of trenches required for an HGHE to cover 100% of peak heating loads and 60% of peak cooling loads and; **(3)** the percentage of heating and cooling peak loads that can be covered by an HGHE located under the greenhouse with the similar dimensions. The two first scenarios represent more conventional systems while the third shows what percentage of the loads can be covered if the facility is limited in space and must install the HGHEs under the greenhouse.

3. Results

Only samples 3 and 4 were considered since the density of samples 1 and 2 was not representative of the soil composing the field. Laboratory results are shown in Table 3.

Table 3. Laboratory results for soil thermal properties

	Soil thermal conductivity (W m^{-1} K^{-1})			Soil thermal diffusivity (mm^2 s^{-1})			Soil volumetric heat capacity (J K^{-1} m^{-3})	
Sample	**Measures**	**Average**	**Corrected average**	**Measures**	**Average**	**Corrected average**	**Measures**	**Average**
3	1.080	1.081	1.083	0.433	0.427	0.419	1.852	1.881
	1.080			0.422			1.910	
	1.084			0.425			1.898	
	1.080			0.426			1.886	
				0.428			1.875	
				0.430			1.865	
4	1.298	1.289	1.317	0.561	0.561	0.577	2.667	2.656
	1.294			0.558			2.665	
	1.288			0.562			2.660	
	1.284			0.561			2.653	
	1.285			0.563			2.648	
	1.286			0.561			2.642	
Average			1.200			0.498		2.268

The sizing calculations results are shown in Table 4 and are illustrated in Figure 3. Here, it is important to understand that the largest required space in between that needed for heating versus cooling is prioritized since the system must be able to cover both heating and cooling loads. Therefore, the required space for scenario 1, 2 and 3 is around 414.4 m^2, 326.4 m^2 and 174.4 m^2, respectively. Results for the third scenario show that with an HGHE taking 1.5 times the greenhouse's size, it is possible to cover 40% of peak heating loads and 30% of peak cooling loads, which covers around 67% of total heating and 40% of total cooling in this case. Please note that to simplify the illustration, the greenhouse in Figure 3 is set in a countryside and not in an urban environment.

Table 4. Required space for the three scenarios

Scenario	Peak loads covered	System	Required space (m)	Comparison with greenhouse size of 116 m^2 (%)
1	100%	Heating	40.8 x 8 (326.4 m^2)	281%
	100%	Cooling	51.8 x 8 (414.4 m^2)	357%
2	100%	Heating	40.8 x 8 (326.4 m^2)	281%
	60%	Cooling	34.8 x 8 (278.4 m^2)	240%
3	40%	Heating	21.8 x 8 (174.4 m^2)	150%
	30%	Cooling	18.8 x 8 (148.8 m^2)	128%

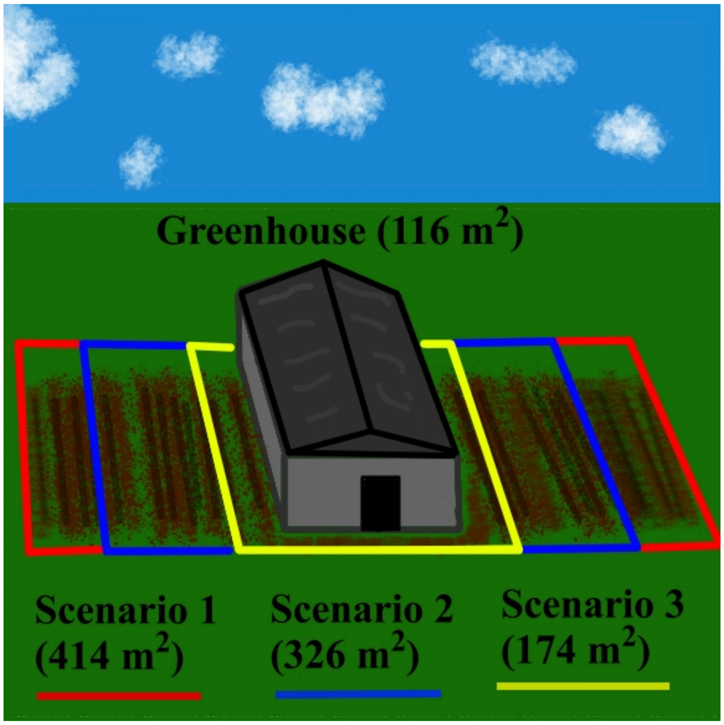

Figure 3. Required space for the three scenarios compared with the greenhouse

4. Discussion

The results show that designing a geothermal heat pump system to cover the entirety of the heating and cooling loads of a greenhouse requires a lot of space for HGHE, which is not optimal for urban areas. There is a considerable reduction of surface area needed with scenario 2 that would involve an auxiliary cooling system, but this much space can also be difficult to find in some cases. Scenario 3 is well adapted to the space available but implies that the greenhouse will have to use auxiliary systems to both heat and cool the building. Lazzarin (2020) gives some insights on solar assistance of heat pumps by PV/T collectors, that offer both electricity to drive the heat pump and a solar assistance to the heat pump cold source. Coupling a ground source and a solar section therefore appear to be an interesting approach, since solar heat can also recharge the ground in periods of low or no heating demand. Zhou et al. (2020) also propose a model for a solar assisted heat pump system that functions well even under low radiation conditions, showing that solar panels, water tank and evaporator of the heat pump can be connected in series in order to reduce the inlet temperature of the solar panels, which would improve the energy efficiency. If the greenhouse is looking to reduce installation costs as much as possible, there is also the alternative of using the GSHP to cover partly the heating and cooling loads and to use their original system to cover the loads during high demand periods.

Figure 3 shows that in the case of an urban greenhouse, it is quite difficult to both save space and be cost efficient, as HGHEs can only partly cover the greenhouse's consumption for heating and cooling if they are installed as shown in scenario 3. Sizing calculations for the third scenario's do not consider the fact that most of the HGHE is located under the greenhouse, which affects the conditions above the ground since the software GLHEPro does not consider heat transfer between building and subsurface components of the system. Hence, third scenario's results give an idea of the space required for such a system but do not accurately consider heat exchanges that could take place at the ground surface under the greenhouse.

It is important to consider that results will vary with different soil's thermal properties, which implies that a soil with a higher thermal conductivity would reduce the required space for the HGHEs and that a soil with a lower thermal conductivity would have the opposite effect.

It would be important to perform numerical simulations of an HGHE located under a greenhouse to understand the impact of having a constant temperature above the system instead of having atmospheric temperature conditions like considered in this study. Surface water infiltration due to plant watering inside the greenhouse and rainfall outside the greenhouse could also change the subsurface thermal properties and effect the efficiency of the system. Work done by Sangi et al. (2018) shows different modelling options and compare their efficiency, which could help to develop a modelling strategy properly considering subsurface flow and heat transfer for HGHE under a greenhouse.

5. Conclusions

The required space for an HGHE to cover the total heating and cooling loads of a 116 m^2 greenhouse in Montreal is equal to 414.4 m^2. The required space for an HGHE to cover 100% of the heating loads and 60% of the peak cooling loads is equal to 326.4 m^2. Installing a HGHE with a limited space of 1.5 times the size of the greenhouse leads to a coverage of 40% of the peak heating loads and 30% of the peak cooling loads. While results conclusively show that

HGHEs installed only under the greenhouse are not covering a major part of the heating and cooling consumption, they give an idea of the space required for a small greenhouse to install HGHEs. Therefore, it can be expected that excavations size will be around 2 – 3 times the greenhouse size for geothermal heat pumps to provide the energy.

Numerical simulations should be made on that system to better evaluate the advantages of installing an HGHE under a greenhouse. Few greenhouses appear to use geothermal heat pump technology because of installation cost, which can be an issue in the agriculture sector providing low income or for community driven projects of underprivileged in urban districts looking for local food supply. Hence, more research should be made to evaluate the maximum amount of energy that can be provided by HGHE of reasonable sizes.

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