Institut national de la recherche scientifique
Reykjavik University

Étude des systèmes de pompe à chaleur géothermique horizontaux pour les serres urbaines du Québec

Study of horizontal geothermal heat pump systems for urban greenhouses in Quebec

Par
Xavier Léveillée-Dallaire

INRS - Maîtrise en sciences de la Terre (bidipl. INRS-Univ. De Reykjavik, énergie renouvelable) – 2017

Reykjavik University – Sustainable energy engineering

Président du jury et Examinateur interne	John Molson Université Laval
Examinateur externe	Árni Ragnarsson Iceland Geosurvey
Directeur de recherche	Jasmin Raymond INRS – Centre-Eau-Terre-Environnement
Directeur de recherche	Jónas Þór Snæbjörnsson Reykjavik University

Remerciements

Je tiens à remercier mon directeur de recherche Jasmin Raymond pour m'avoir conseillé, supporté et aidé tout au long de ce projet. Merci énormément de m'avoir encouragé dans mes projets et voyages, qui ont fait de cette maîtrise une expérience absolument enrichissante autant au niveau professionnel, académique que culturel. Tu étais le meilleur superviseur que je pouvais avoir.

Merci à Fujii sensei qui m'a accueilli à l'Université d'Akita pendant deux mois pour que j'y réalise un stage de recherche. ふじい先生、秋田で私を歓迎してくださり、また様々な景色を見せてくださり本当にありがとうございました.

I would like to thank my codirector Jónas Þór Snæbjörnsson for his guidance, which helped improve the quality of my work as well as for being an excellent guide in Tallinn. Takk fyrir!

Merci à Hubert, Nicolò et Félix-Antoine qui m'ont aidé à de multiples reprises quand j'ai fait face à des problèmes dans mes projets.

Résumé

Tout au long de l'histoire, l'agriculture urbaine a été considérée comme une solution à la sécurité alimentaire et aux perturbations des chaînes d'approvisionnement alimentaire mondiales, tout en permettant la production de légumes locaux. Les changements climatiques et le réchauffement de la planète étant principalement dus aux gaz à effet de serre (GES), il est très important de chauffer et de refroidir les serres urbaines dans une optique de développement durable, en utilisant des technologies telles que les systèmes de pompes à chaleur géothermiques. Les échangeurs de chaleur géothermiques horizontaux (ÉCGHs) à serpentin constituent une alternative à explorer pour réduire les coûts de chauffage et de climatisation de serres tout comme l'émission de GES. Par ailleurs, le coût d'installation de ces systèmes serait plus abordable que celui des systèmes d'ÉCG conventionnels. L'objectif de cette étude est d'évaluer le potentiel des ÉCGHs dans le chauffage et le refroidissement des serres urbaines considérant les avantages qu'offre l'installation du système sous la serre pour économiser de l'espace et potentiellement augmenter leur performance. Nous posons l'hypothèse que des ÉCGH installés sous une serre bénéficieraient d'un sol ayant une température plus élevée que si le système était installé à côté d'une serre bien que l'ÉCGH ne pourrait couvrir l'ensemble des besoins de chauffage et de climatisation.

Des calculs de dimensionnement ont d'abord été effectués pour les ÉCGHs d'une serre de 7.62 m x 15.24 m située sur l'île de Montréal, où la consommation d'énergie annuelle, mensuelle et horaire a été estimée à partir de simulations de bâtiments antérieurs. Trois scénarios ont été utilisés pour réaliser ce calcul qui vise à déterminer le nombre et la longueur d'excavation requise selon les charges de chauffage et de climatisation couvertes en période de pointe; soit (1) 100 % des charges de refroidissement et de chauffage; (2) respectivement 100 % et 60% des charges de chauffage et de refroidissement et; (3) un pourcentage de charges variables en fonction d'un ÉCGH ayant des dimensions similaires à la serre, soit environ 116 m^2. Les dimensions estimées de l'excavation pour les cas 1 et 2 sont de 414 m^2 et 326.4 m^2. Le pourcentage estimé des charges de pointe couvertes pour le cas 3 est de respectivement 40 % et 30% des charges chauffage et de refroidissement.

En utilisant des données historiques de température atmosphérique, un profil de consommation d'énergie d'une serre en conception à La Pocatière (Québec, Canada) et des mesures des propriétés thermiques du sol, des simulations numériques réalisées par éléments finis avec FEFLOW v. 7.5 ont permis de déterminer quelle part des charges de chauffage et de refroidissement peut être couvertes si les ÉCGHs sont uniquement installés sous la serre. C'est à cette étape que l'effet d'une température constante au-dessus des ÉCGH et causée par la serre a pu être considéré. Les simulations ont impliqué quatre scénarios comparés à un cas de base. L'étude confirme qu'un minimum de 7.1 % et 26.5 % des charges totales de chauffage et de refroidissement d'une petite serre est couvert après un an d'opération avec un ÉCGH à une profondeur de 1.5 m sans serre au-dessus. En revanche, l'installation de ce même ÉCGH sous une serre à température constante de 21 °C fait passer les charges de chauffage couvertes à 22.8 % et les charges de refroidissement couvertes à 24.2 %. L'analyse de sensibilité indique que la température constante de la serre réduit la dépendance du système à l'égard de la température ambiante pour le chauffage et le refroidissement, même si le refroidissement est moins efficace.

Abstract

Throughout history, urban agriculture has been seen as a solution to food security and disruptions in global food supply chains, while allowing to produce vegetables locally. With climate change and global warming primarily driven by greenhouse gases, heating and cooling urban greenhouses in a sustainable manner is very important, using technologies such as geothermal heat pump systems. Horizontal geothermal heat exchangers (HGHEs) with coils are an alternative to be explored to reduce greenhouse heating and cooling costs as well as greenhouse gas emissions. Moreover, the installation cost of these systems would be more affordable than that of conventional GHE systems. The objective of this study is to evaluate the potential of HGHEs in heating and cooling urban greenhouses considering the benefits of installing the system under the greenhouse to save space and potentially increase their performance. We assume that a HGHE installed under a greenhouse would benefit from a higher soil temperature than if the system were installed next to a greenhouse, although the HGHE would not be able to cover all the heating and cooling needs.

Sizing calculations were first performed for the HGHEs of a 7.62 m x 15.24 m greenhouse located on the island of Montreal, where the annual, monthly, and hourly energy consumption was estimated from simulations of previous buildings. Three scenarios were used to perform this calculation to determine the number and length of excavations required based on the heating and cooling loads covered during peak periods; (1) 100% of the cooling and heating loads; (2) 100% and 60% of the heating and cooling loads, respectively; and (3) a percentage of variable loads based on a HGHE with similar dimensions to the greenhouse, i.e., approximately 116 m^2. The estimated dimensions of the excavation for cases 1 and 2 are 414 m^2 and 326.4 m^2. The estimated percentage of peak loads covered for case 3 is 40% and 30% of the heating and cooling loads, respectively.

Using historical atmospheric temperature data, an energy consumption profile of a greenhouse under design in La Pocatière (Quebec, Canada) and measurements of the thermal properties of the soil, finite element simulations performed with FEFLOW v. 7.5 were used to determine how much of the heating and cooling loads can be covered if the HGHEs are installed only under the greenhouse. It was at this stage that the effect of a constant temperature above the HGHEs and caused by the greenhouse could be considered. The simulations involved four scenarios compared to a base case. The study confirms that a minimum of 7.1% and 26.5% of the total heating and cooling loads of a small greenhouse are covered after one year of operation with a HGHE at a depth of 1.5 m without a greenhouse above. In contrast, installing the same system under a greenhouse with a constant temperature of 21°C increases the covered heating loads to 22.8% and the covered cooling loads to 24.2%. The sensitivity analysis indicates that the constant greenhouse temperature reduces the system's dependence on ambient temperature for heating and cooling, even though cooling is less efficient.

Samantekt

Í gegnum söguna hefur landbúnaður í þéttbýli skapað aukið fæðuöryggi og dregið úr truflunum í alþjóðlegum matvælaframboðskeðjum, meðal annars með framleiðslu matjurta í gróðurhúsum. Með loftslagsbreytingum og hlýnun jarðar sem aðallega er knúin áfram af gróðurhúsalofttegundum er mikilvægt að hita og kæla þéttbýlisgróðurhús á sjálfbæran hátt með því að nota tækni eins og jarðhitadælukerfi. Lárétt jarðhitaskipti (HGHE) með lagnavafningum eru valkostur sem vert er að kanna til að draga úr kostnaði við hitun og kælingu gróðurhúsa sem og losun gróðurhúsalofttegunda. Ekki síst ef uppsetningarkostnaður slíks kerfs er hagkvæm í samanburði við hefðbundnar varmaskipta aðferðir. Markmið þessarar rannsóknar er að meta möguleika HGHE við upphitun og kælingu þéttbýlisgróðurhúsa með hliðsjón af ávinningi af því að setja kerfið undir gróðurhúsið til að spara pláss og mögulega bæta nýtni. Við gerum ráð fyrir að HGHE sem sett er upp, undir gróðurhúsi myndi njóta góðs af hærri jarðvegshita en ef kerfið væri sett upp við hliðina á gróðurhúsi, jafnvel þó að HGHE myndi ekki geta uppfyllt alla upphitunar- og kælingarþörf.

Stærðarútreikningar fyrir láréttan jarðvarmaskipti (HGHE) voru fyrst gerðir fyrir 7.62 m x 15.24 m gróðurhús sem staðsett er á eyjunni Montreal: Meðalgildi orkunotkunar var áætlað fyrir hvern klukkutíma, hvern mánuð og hvert ár, út frá hermunum af fyrri byggingum. Þrjú svið voru notuð til að framkvæma þennan útreikning til að ákvarða umfang uppgraftar sem krafist er miðað við það upphitunar- og kælingarálag sem kerfið á að geta uppfyllt á álagstímum; (1) 100% af bæði kælingar og upphitunarálagi; (2) 100% af upphitunarálagi og 60% af kælingarálagi; (3) hlutfall breytilegs álags miðað við HGHE með svipuðum stærðum og gróðurhúsið, þ.e.a.s. um það bil 116 m^2. Áætluð mál uppgröftsins í tilvikum 1 og 2 eru 414 m^2 og 326.4 m^2. Áætlað hlutfall hámarksálags sem fjallað er um í tilviki 3 er 40% upphitunarálagi og 30% af kælingarálagi.

Með því að nota söguleg gögn um hitastig andrúmsloftsins, orkunotkun gróðurhúsa í hönnun í La Pocatière (Quebec, Kanada) og mælingar á hitauppstreymi jarðvegs, voru gerðar hermanir með FEFLOW v. 7.5 til að ákvarða hversu mikið af upphitunar- og kælingarálagi er hægt að uppfylla ef HGHE er aðeins sett upp undir golfi gróðurhússins. Það var á þessu stigi sem hægt var að huga að áhrifum stöðugs hitastigs yfir HGHE á gróðurhúsið. Hermanirnar fólu í sér fjórar sviðsmyndir sem voru bornar saman við grunntilfelli. Rannsóknin staðfestir að eins árs notkun með HGHE á 1.5 m dýpi undir óupphituðu gróðurhúsi gefur að lágmarki 7.1% af heildarhitunarþörf og 26.5% af kælingarþörf. Aftur á móti, ef sama HGHE-kerfið er sett undir gróðurhús með stöðugu hitastigi 21 °C, þá getur kerfið gefið 22.8% af hitunarþörfinni og 24.2% af kælingarþörfinni. Næmnigreiningin gefur til kynna að stöðugur gróðurhúsahiti dragi úr áhrifum umhverfishita á upphitun og kælingu, jafnvel þó aðeins dragi úr skilvirkni kælingar.

Avant-propos

Ce mémoire de maîtrise est constitué d'une synthèse comprenant deux chapitres de travaux de recherche. Le chapitre 1 décrit des calculs de dimensionnement réalisés pour une serre à Montréal et correspond à un article de conférence publié lors de la conférence annuelle de Geothermal Rising à Reno, États-Unis, en 2022. Dans ce chapitre, les calculs visent à déterminer l'espace requis pour installer des ÉCGHs couvrant l'ensemble des besoins en chauffage et en refroidissement d'une serre de 8 m par 15 m, ainsi qu'à déterminer le pourcentage de ces besoins pouvant être couvert par un système de même superficie. Les résultats ne prennent pas en compte l'effet de la température constante de la serre sur le système, mais permettent d'obtenir des résultats préliminaires qui ont pu être comparés avec les simulations numériques réalisées dans le chapitre 2. Celui-ci est un article scientifique prêt à être soumis incluant des simulations numériques visant à étudier le potentiel des ÉCGHs installés sous une serre et à étudier l'impact de la température constante de la serre sur ce système. Ces deux chapitres témoignent des travaux réalisés dans le cadre de ce projet de maîtrise.

- Chapitre 1 : Article de conférence présenté lors de la conférence annuelle de Geothermal Rising en 2022. ***Sizing horizontal geothermal heat exchangers for community greenhouses in Montreal.***

- Chapitre 2: Article prêt à soumettre. ***Performance assessment of horizontal ground heat exchangers installed under a greenhouse in Quebec, Canada.***

Table des matières

Liste des figures

Liste des tableaux

Nomenclature

Lettres latines

	Français	English	Units
Co	Nombre de Courant	Courant number	
Cp	Capacité thermique	Heat capacity	(J kg^{-1} K^{-1})
d	Diamètre	Diameter	(m)
E	Énergie interne	Internal energy	(J kg^{-1})
g	Accélération de la gravité	Acceleration due to gravity	(m s^{-2})
j_T	Vecteur du flux de chaleur fouriérien	Fourierian heat flux vector	(W m^{-2})
k	Tenseur de perméabilité	Permeability tensor	(m^2)
L	Longueur	Length	(m)
m'	Débit	Flow rate	(kg s^{-1})
N	Nombre d'anneaux	Number of rings	
Pe	Nombre de Peclet	Peclet number	
q	Taux de transfert de chaleur par longueur de tranchée	Heat injection rate per unit length	(W m^{-1})
Q	Charge	Load	(W)
Q_T	Source de chaleur	Source of heat	(J s^{-1})
$Q\rho$	Puits/source de masse fluide	Fluid mass sink/source	(s^{-1})
R	Rayon des anneaux	Ring radius	(m)
Re	Nombre de Reynolds	Reynolds number	
T	Température	Temperature	(°C)
W	Épaisseur	Width	(m)
x	Coordonnées cartésiennes	Cartesian coordinates	(m)
X	Longueur de la tranchée dans laquelle la bobine HGHE est enterrée	Length of the trench in which the slinky coil HGHE is buried	(m)

Lettres Grecques

Δ	Différence	Difference	
α	Diffusion thermique	Thermal diffusivity	(m^2 s^{-1})
∂	Dérivée partielle	Partial derivative	
ε	Porosité	Porosity	

μ	Viscosité dynamique	Dynamic viscosity	(Pa s)
ρ	Densité	Density	(kg m^{-3})

Indices

Amb	Ambiant	Ambiant
c	Consommation	Consumption
cool	Refroidissement	Cooling
g	Sol	Ground
heat	Chauffage	Heating
in	Entrée	Entering
i, j	Indices spatiaux	Spatial indices
out	Sortie	Exit
s	Sous-surface	Subsurface
ring	Anneau	Ring
α	Indice de phase	Phase index

Abréviations (français)

COP	Coefficient de performance
ÉCGH	Échangeur de chaleur géothermique horizontal
EFT	Température d'entrée du fluide
GES	Gaz à effet de serre
GSHP	Pompe à chaleur géothermique
LFT	Température d'entrée du fluide
TRT	Test de réponse thermique

Abbreviations (English)

COP	Coefficient of performance
EFT	Entering fluid temperature
GES	Greenhouse gases
GSHP	Ground source heat pump
HGHE	Horizontal ground heat exchanger
LFT	Leaving fluid temperature
TRT	Thermal response test

I. Synthèse

1. Introduction

L'agriculture urbaine s'est développée tout au long de l'histoire, en particulier en période de crise, où les habitants en sont venus à cultiver des fruits et des légumes dans des jardins communautaires ou personnels afin d'avoir accès à une source directe de nourriture (McClintock, 2010). La pandémie de COVID-19 est un bon exemple d'une telle crise mondiale qui a exacerbé le phénomène d'insécurité alimentaire parmi les populations vulnérables des grandes villes (Gundersen et al., 2021). Face aux perturbations des chaînes d'approvisionnement alimentaire mondiales et aux préoccupations croissantes en matière de sécurité alimentaire, l'agriculture urbaine est apparue comme un moyen de résoudre en partie ces problèmes et de permettre la production de denrées fraîches et locales. Bien que cela réduise les insécurités alimentaires et augmente le bien-être social, il existe des coûts élevés et des contraintes associées (Mok et al., 2014). Le statut socio-économique des citoyens et l'accès à un terrain sur lequel le jardinage personnel est possible sont deux contraintes importantes qui font que les jardins personnels ne sont accessibles qu'à une certaine partie de la population (Schupp, 2017). Par conséquent, les entreprises sociales, les organisations communautaires et les initiatives municipales jouent un rôle clé dans l'amélioration de la sécurité alimentaire dans les zones urbaines défavorisées (Bach & McClintock, 2021). Envisager le développement d'initiatives d'économie sociale peut contribuer à la sécurité alimentaire dans les quartiers.

Différents types d'agriculture urbaine peuvent être utilisés au profit d'une communauté. Les types suivants sont courants : jardins d'arrière-cour, aménagement paysager des rues, jardins tactiques, serres, jardinage forestier, jardins sur les toits, murs verts, fermes verticales, élevage d'animaux, apiculture urbaine et aquaponie (Spacey, 2017). Les coûts et les contraintes varient considérablement selon le type choisi, et ces types d'agriculture peuvent être résidentiels, commerciaux ou communautaires.

Les serres sont de plus en plus populaires pour l'agriculture en raison de leur rendement élevé, qui est 10 à 20 fois plus élevé par unité de surface que la production en plein air (Ahamed et al., 2019). Cependant, le maintien d'une température contrôlée dans ces environnements nécessite des coûts énergétiques importants. Pour éviter d'endommager les plantes, la température doit rester dans une fourchette spécifique, sans variation supérieure à 5-7°C (Mohamed, 2003). Par conséquent, la majeure partie de l'énergie consommée par les serres est destinée au chauffage, le reste étant utilisé pour les appareils électriques et le transport (Zhang et al., 2020). Cela représente un défi important pour les serristes des régions froides, qui doivent trouver des moyens économiques et environnementaux pour couvrir leurs besoins en chauffage.

Il est largement reconnu que les changements climatiques et le réchauffement de la planète sont dus aux gaz à effet de serre (GES), principalement de nature anthropique. Par conséquent, la réduction des émissions de CO_2 devient l'une des principales nécessités et préoccupations (IPCC, 2014). Par conséquent, la transition vers des énergies durables est d'une grande importance pour réussir la décarbonisation du secteur de l'énergie. Il est donc important de chauffer et de refroidir les serres urbaines en pensant à la durabilité environnementale; les opérateurs réduiront du même coup leur vulnérabilité aux fluctuations des prix et aux perturbations de l'approvisionnement en énergie fossile (De Rosa et al., 2022), en plus d'améliorer la perceptions du public à leur égard. L'utilisation des énergies renouvelables peut améliorer leur image publique et leur réputation de producteurs de denrées alimentaires respectueux de l'environnement.

Les pompes à chaleur géothermiques constituent la plus garde partie des applications géothermiques qui font une utilisation directe de la chaleur, avec 71.6 % de la capacité installée et 59.2 % de la consommation annuelle d'énergie en 2020 (Lund et al., 2020). Cependant, ces systèmes ont un coût d'installation plus élevé que les systèmes de chauffage traditionnels (Farabi-Asl et al., 2018). Il existe trois principaux types de systèmes de pompes à chaleur géothermiques : les pompes à chaleur d'aquifère, les pompes à chaleur d'eau de surface et les pompes à chaleur couplées au sol. La boucle ouverte des aquifères et des eaux de surface consiste à faire circuler l'eau d'un aquifère, d'un lac ou d'un étang, mais cette méthode est moins répandue car elle nécessite une source d'eau à proximité. Les pompes à chaleur couplées au sol sont dotées d'échangeurs de chaleur en circuit fermé, généralement installés dans des trous de forage ou des tranchées. Les systèmes verticaux nécessitent un forage pour insérer les tuyaux dans le sol, ce qui en fait une option peu encombrante, et bénéficie de l'inertie thermique du sol qui maintient une température constante à une certaine profondeur. Les systèmes horizontaux sont constitués de tuyaux enterrés dans des tranchées à une profondeur d'environ 1.5 m, où circule de l'eau ou un mélange d'eau et d'antigel (Chiasson, 2016). La chaleur est extraite ou injecté via le fluide caloporteur qui circule en circuit fermé et les échanges thermiques avec le sol se font par conduction.

Les échangeurs de chaleur géothermiques horizontaux (ÉCGHs) à serpentin sont une méthode rentable pour réduire les coûts d'installation des systèmes géothermiques car elle repose sur l'utilisation d'une exactrice pour aménager des tranchées peu profondes au lieu d'une foreuse pour les trous de forage. Cependant, ce type de système géothermique nécessite un espace important pour enterrer les tuyaux des échangeurs de chaleur, ce qui rend plus difficile l'installation dans les endroits où l'espace est limité. Dans ce cas, le système géothermique peut être couplé à un autre type de système de chauffage ou le taux d'échange de chaleur par unité de surface peut être amélioré en optimisant la conception du système (Fujii et al., 2012, 2013; Léveillée-Dallaire et al., 2022). Les serres peuvent être compatibles avec ce type de système géothermique, puisque le plancher est souvent composé du sol meuble en place, ce qui facilite l'accessibilité au système.

2. Problématique

Afin de répondre aux changements climatiques et d'encourager la réduction d'émissions de CO_2, il est important de promouvoir les sources d'énergie renouvelable pour le chauffage et refroidissement des bâtiments. Pour ce faire, ce projet évalue le potentiel des ÉCGHs à couvrir les charges de chauffage et de climatisation des serres, ainsi que de considérer un moyen de réduire les coûts d'installation afin de rendre ce type de système accessible même aux serres communautaires, qui doivent généralement opérer avec un budget restreint. Pour tenter de proposer un système avec un coût d'installation abordable, seuls les ÉCGHs en serpentin sont ici étudiés.

Les taux d'échange de chaleur par unité de longueur des tuyaux d'échange de chaleur horizontaux droits sont nettement inférieurs à ceux obtenus avec un échangeur de chaleur souterrain vertical, étant donné que les températures dans le sol peu profond présentent des variations saisonnières et que les sols secs près de la surface ont une conductivité thermique relativement faible (Williams & Gold, 1977). L'utilisation de tuyaux en serpentin au lieu de tuyaux droits est donc une bonne alternative pour collecter plus d'énergie par unité de longueur de tranchée, ce qui peut faciliter l'application d'un tel système, même dans les cas où la disponibilité de terrain est limitée (Fujii et al., 2012). Cette configuration permet donc de réduire l'espace et par conséquent les coûts de tranchées.

Jusqu'à présent, peu d'études ont été réalisées sur les systèmes de chauffage et de climatisation situés sous une bâtiment comme une serre, en particulier en milieu urbain, bien qu'il s'agisse d'un moyen de lutter contre les émissions de GES et l'insécurité alimentaire dans les villes. Il est donc important d'évaluer l'effet de la serre sur un tel système en considérant les propriétés thermiques du sol, la température ambiante et la consommation d'énergie du bâtiment. La plupart des études (Chiriboga et al., 2021; Morshed et al., 2022) sur les serres à haut rendement ont été menées pour évaluer les performances d'un tel système dans un environnement spécifique, sans étudier les scénarios réalistes. Chaque site étudié dans ce projet a ainsi fait l'œuvre de travaux de caractérisation pour connaître les propriétés thermiques du sol et des profils de charges anticipés pour ces serres déterminées par des simulations énergétiques de bâtiments ont été considérés pour fournir des informations et des conseils applicables à la sériculture réalisée dans le climat québécois.

Dans les zones urbaines, il n'y a pas beaucoup d'espaces ouverts ou de terrains qui peuvent être utilisés pour mettre en œuvre les systèmes de chauffage, de ventilation et de climatisation. Il est donc important de savoir s'il est possible d'installer le système sous la serre étudiée pour couvrir les charges de chauffage et de refroidissement, ainsi que de déterminer quel pourcentage des charges peut être couvert par ces systèmes, en fonction de l'espace libre. Ici, nous émettons l'hypothèse qu'un ÉCGH couvrant une zone limitée située sous la serre pourrait être plus performant mais ne couvrira pas la totalité des charges de chauffage ou de refroidissement de la serre. Pour vérifier cette hypothèse, des calculs initiaux ont été effectués à l'aide du logiciel GLHEPro. Ces calculs de dimensionnement ont été effectués pour un ÉCGH à serpentin, en considérant des données historiques de température en périphérie de Montréal ainsi que le profil de consommation d'énergie pour le chauffage et la climatisation d'une serre située à Montréal.

Dans le cadre du deuxième chapitre, des simulations numériques ont été effectuées pour une serre en cours de conception située à La Pocatière, en utilisant des données historiques de température pour cette région ainsi qu'un profil de consommation énergétique spécifique pour la serre. Les valeurs des propriétés thermiques du sol sous la serre ont également été prises en compte dans les simulations, qui ont été réalisées en suivant les travaux précédemment effectués par Fujii et al. (2012 ; 2013). Les conditions aux limites ont été modifiées par rapport au travail de Fujii pour considérer la présence d'une serre avec une frontière à température constante au-dessus des ÉCGHs.

Ce travail se divise en deux parties. La première partie (Chapitre 1) cherche à donner une idée des dimensions requises pour qu'un système d'ÉCGHs en serpentin puisse couvrir les charges de chauffage et de refroidissement d'une serre située dans la ville de Montréal et d'étudier l'alternative d'installer ce système sous une serre pour économiser de l'espace. Des calculs analytiques relativement simples ont été effectués sans considérer l'effet de la serre sur la température du sol. La deuxième partie (Chapitre 2) vise à offrir des réponses semblables mais avec des travaux de modélisations numériques plus poussés considérant l'effet de la serre sur la température du sol pour déterminer quelle part des charges de chauffage et de climatisation peuvent être couvertes par les ÉCGHs sous la serre. Le travail a été réalisé dans le cadre d'une étude multidisciplinaire visant à fournir des technologies vertes abordables aux organisations communautaires qui exploitent des serres avec des moyens limités (COMMUNOSERRE, 2022).

Les deux chapitres se basent sur des serres différentes. Un profil de consommation énergétique d'une serre en opération à Montréal a été considéré dans le premier chapitre, tandis qu'un profil de consommation d'énergie d'une serre en conception à La Pocatière a été considéré dans le deuxième chapitre (Enerprox, 2022; Lalonde et al., 2021; Léveillé-Guillemette & Monfet, 2018). La serre étudiée au premier chapitre a été modélisée dans TRNSYS. Le model a été calibrée à l'aide de sa consommation mensuelle de gaz et des mesures de la température de l'air intérieur et de l'humidité relative. Le logiciel EnergyPlus et l'interface utilisateur OpenStudio V2.2 ont été utilisés pour développer le modèle de bâtiment. Développer de tels modèles est complexe en raison des multiples facteurs à considérer, tels que la gestion de l'humidité, la croissance des plantes et l'effet de l'ensoleillement dans le bâtiment. Le Cégep de La Pocatière prévoit la construction d'une serre fermée et de bâtiments de recherche complémentaires. Le projet vise à démontrer qu'un tel complexe de recherche peut être chauffé et climatisé principalement à l'aide de sources d'énergie renouvelables telles que des systèmes de pompes à chaleur géothermique. Un système de chauffage hybride est envisagé et les pompes à chaleur géothermique seraient installées sous la serre pour minimiser les coûts d'installation, sachant que le système ne peut répondre qu'à une partie des besoins de chauffage et de refroidissement. Des sources de chauffage et de refroidissement auxiliaires seraient nécessaires pour couvrir la totalité des charges de chauffage et de refroidissement de la serre. La serre étudiée dans ce chapitre a été modélisée avec la fonction Visual Basic for Applications de Microsoft, puis validée avec le logiciel HortinEnergy. Différents facteurs tels que le chauffage, déshumidification sans apport d'air et l'accumulation thermique ont été étudiés par la firme afin de réaliser une analyse énergétique pour le bâtiment (Enerprox, 2022).

3. Objectifs

Ce projet de maîtrise vise à :

1. Évaluer le potentiel des systèmes de chauffage et de refroidissement géothermique des serres urbaines et explorer l'alternative d'installer les ÉCGHs sous la serre pour économiser de l'espace et par conséquent offrir un système abordable;
2. Déterminer dans quelle mesure les charges de chauffage et de refroidissement peuvent être couvertes si les échangeurs de chaleur sont uniquement installés sous une serre;
3. Étudier l'impact de la température constante d'une serre sur la performance d'un système d'ÉCGH, dans le cas où le système est installé sous la serre.

4. Approche Méthodologique

Afin de réaliser ces objectifs, la méthodologie associée à chaque objectif a été définie comme suit :

1.
    - Campagne d'échantillonnage à Montréal pour mesurer les propriétés thermiques du sol en laboratoire.
    - Recherche d'un profil de consommation d'énergie pour une serre à Montréal.
    - Réaliser des calculs de dimensionnement avec le logiciel GLHEPRO pour divers scénarios de charges couvertes et d'espace requis.

2.
    - Développement de modèles numériques pour simuler l'opération d'un ÉCGH en utilisant la méthode de Fujii et al., (2012 ; 2013), en limitant l'espace pris par l'échangeur de chaleur à la surface couverte par la serre.
    - Analyser les résultats de simulation pour une durée de 5 ans.
    - Comparer les charges de chauffage et de climatisation produites par le système avec un profil de consommation d'énergie pour une serre en conception à La Pocatière.

3.
    - Développement de modèles numériques représentant différents scénarios pour simuler l'opération d'un ÉCGH en utilisant la méthode de Fujii et al., (2012 ; 2013).
    - Simuler le système avec et sans présence de serre au-dessus de l'ÉCGH.
    - Comparer les charges de chauffage et de climatisation produites par le système avec un profil de consommation d'énergie pour une serre en conception à La Pocatière.
    - Comparer le coefficient de performance (COP) de la pompe à chaleur simulée dans les différents scénarios.

II. Articles

Chapitre 1

Sizing horizontal geothermal heat exchangers for community greenhouses in Montreal

Titre traduit

Dimensionnement d'échangeurs géothermiques horizontaux pour des serres communautaires à Montréal

Auteurs

Xavier Léveillée-Dallaire [a], Jasmin Raymond [a], Hikari Fujii [b], and Shunsuke Tsuya [b]

[a] Centre Eau Terre Environnement, Institut national de la recherche scientifique, Canada

[b] Graduate School of International Resource Sciences, Akita University, Akita, Japan

Publié

Geothermal Rising Conférence 2022 – Reno, USA

Transactions Volume 46. P. 793 - 803

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.

1.1 Introduction

Environmentally controlled agricultural techniques such as cultivation in greenhouses are becoming more and more popular due to their high output, which is 10 – 20 times greater per unit area than outdoor production (Ahamed et al., 2019). 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 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 et al., 2020). Reducing heating costs is a big challenge for greenhouse growers, especially when located in colder regions.

It is widely known that climate change 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 challenges (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 a 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 sufficient 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, 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 type of 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 the 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. An effort was thus made to minimize HGHE length.

1.2 Materials and methods

1.2.1 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 the 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. Lawrence 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 (Lepage, 1996; Nadeau, 2019; Prest & Keyser, 1982). Sediment thickness varies from a few meters to more than 25 meters. The east coast generally shows a more significant 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 average depth of the water table relative to the ground is 4.2 m but this varies with the location (Savard, 2013). Sediments found on the Island of Montreal are shown in Figure 1.1.

1.2.2 Soil thermal properties

In order to make sizing calculations, the soil thermal properties must be evaluated on the various studied sites. To do so, soil sampling was done on the site appearing on Figure 1.1; 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 the *Institut national de la recherche scientifique (INRS)* laboratories using a K2DPro – Decagon device with both the SH-1 and the TR-1 needles. The SH-1 dual-needle with 3 cm length is used 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% $mJ\ m^{-3}\ K^{-1}$). The TR-1 needle with 10 cm length is used to evaluate thermal conductivity (0.1 to 4.0 ± 10% $W\ m^{-1}\ K^{-1}$; Decagon Devices, Inc., 2016). Every sample was analyzed under in situ and saturated conditions. Measured sample thermal properties were assumed to be the same on their respective site, which will facilitate 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. Comparison with a standard was conducted to correct the measured value before and after every test (Decagon Devices, Inc., 2016).

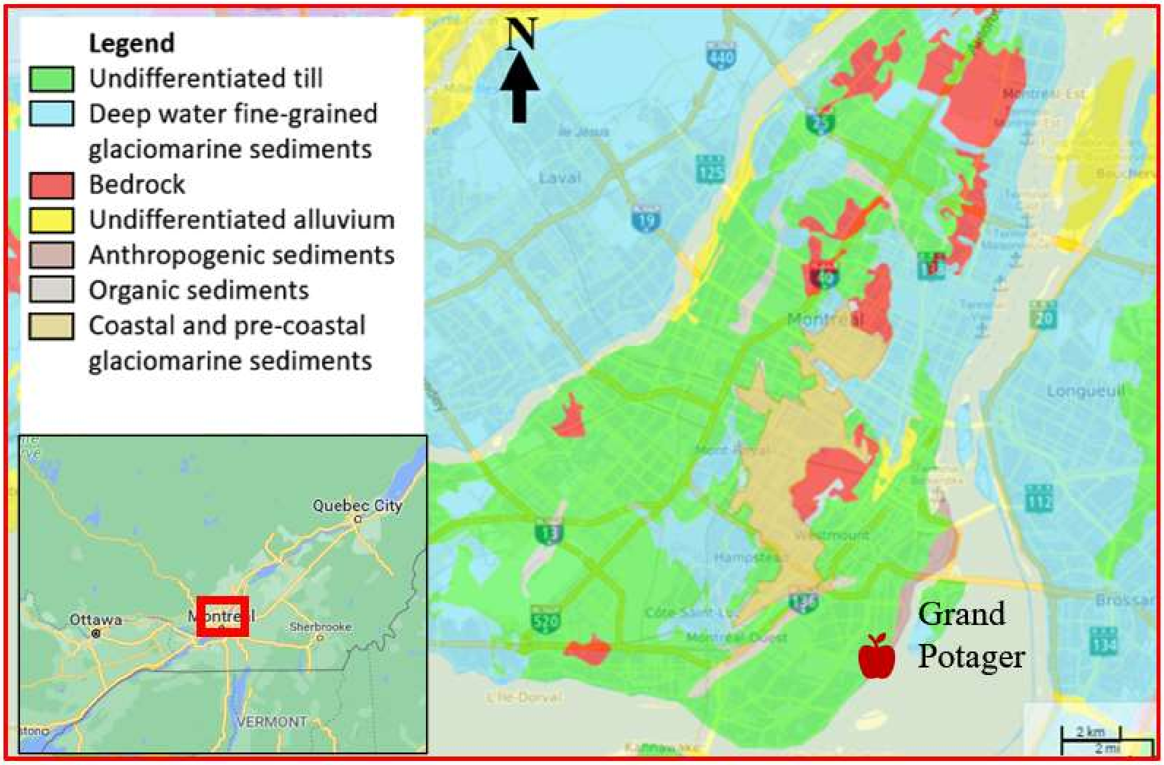

Figure 1.1. Location of Grand Potager greenhouse.

1.2.3 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 $\Delta T(d, t)$ in the ground at time t (s) and distance d (m) from the borehole center is determined according to Marcotte and Pasquier's work (Marcotte & Pasquier, 2009). The quasi-steady state heat transfer rate in terms of fluid transport is given by :

$$2\pi R N_{\text{ring}} q_{\text{ln}} = \dot{m} c_{\text{p}} [T_{\text{in}}(t_{\text{n}}) - T_{\text{out}}(t_{\text{n}})] \quad (1.1)$$

where R is the ring 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).

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 ground surface (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 temperatures 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 (Lalonde et al., 2021; Léveillé-Guillemette & Monfet, 2018). The profile is shown in Figure 1.2. The greenhouse 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 in Table 1.1 and Table 1.2.

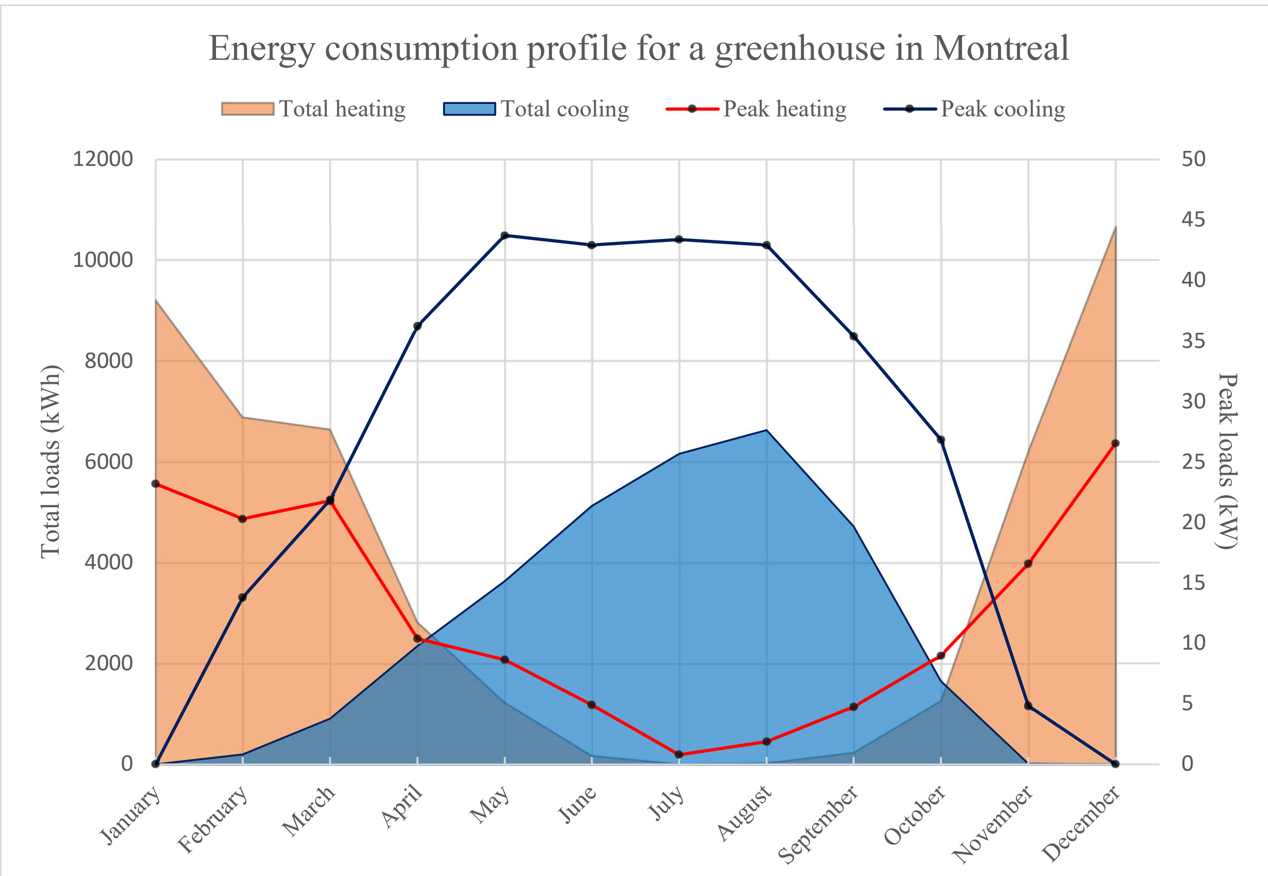

Figure 1.2. Energy consumption profile for a greenhouse in Montreal.

Table 1.1. Sizing calculations inputs.

Sizing calculation 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 1.2. 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 first two 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.

1.3 Results

Only samples 3 and 4 were considered since the density of samples 1 and 2 was not representative of the field site soil. Laboratory results are shown in Table 1.3.

Table 1.3. Laboratory results for soil thermal properties.

Sample	Soil thermal conductivity ($W\ m^{-1}\ K^{-1}$)			Soil thermal diffusivity ($mm^2\ s^{-1}$)			Soil volumetric heat capacity ($J\ K^{-1}\ m^{-3}$)	
	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 calculation results are shown in Table 1.4 and are illustrated in Figure 1.3. 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 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 1.3 is set in a countryside and not in an urban environment.

Table 1.4. 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%

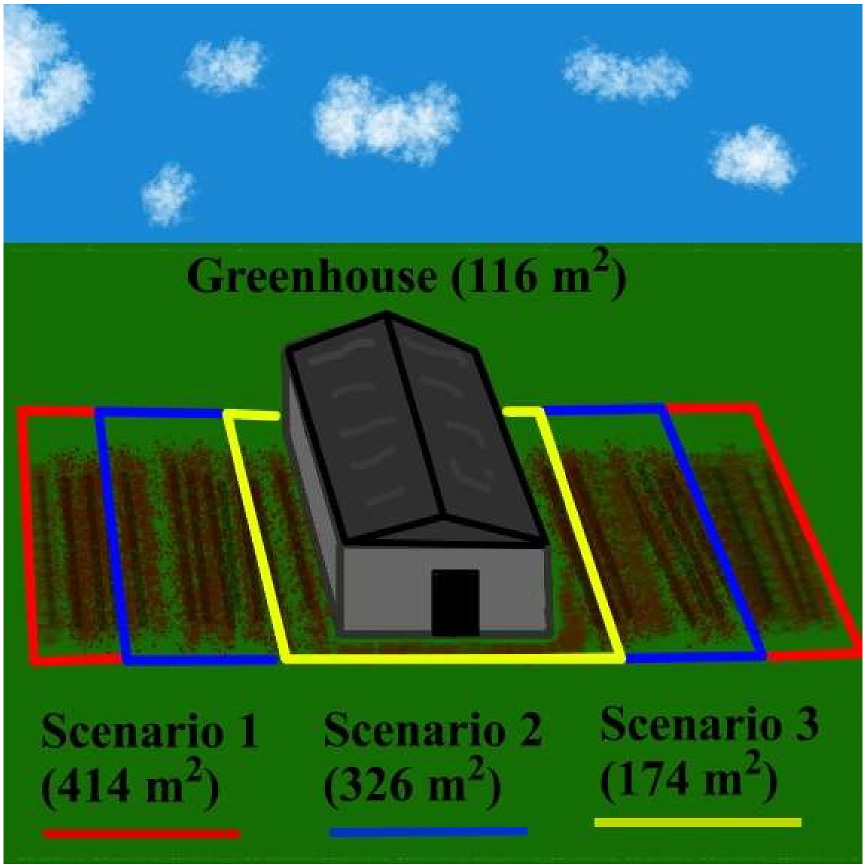

Figure 1.3. Required space for the three scenarios compared with the greenhouse.

1.4 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 (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. (Zhou et al., 2022) 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 partly cover the heating and cooling loads and to use their original system to cover the loads during high demand periods.

Figure 1.3 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 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, results from the third scenario 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 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 those 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. (Sangi & Müller, 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.

1.5 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 do not cover 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 these systems 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 for 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 HGHEs of reasonable sizes.

Chapitre 2

Performance assessment of horizontal ground heat exchangers installed under a greenhouse in Quebec, Canada

Titre traduit

Évaluation de la performance des échangeurs de chaleur souterrains horizontaux installés sous une serre au Québec, Canada

Auteurs

Xavier Léveillée-Dallaire [a], Jasmin Raymond [a], Jónas Þór Snæbjörnsson [b], et Hikari Fujii [c]

[a] Centre Eau Terre Environnement, Institut national de la recherche scientifique, Canada

[b] Iceland School of Energy, Reykjavik University, Iceland

[c] Graduate School of International Resource Sciences, Akita University, Akita, Japan

Article prêt à soumettre

Ce deuxième chapitre de l'étude s'inscrit dans la continuité du premier, qui portait sur les calculs de dimensionnement pour un système d'échangeurs de chaleur horizontaux visant à répondre aux besoins de chauffage et de refroidissement d'une serre à Montréal, tout en cherchant à minimiser l'espace pris par le système. Dans ce deuxième chapitre, des simulations numériques ont été réalisées pour approfondir cette idée et étudier l'impact de la température constante dans une serre sur la performance d'un tel système d'échangeurs de chaleur horizontaux. L'objectif était également d'évaluer la faisabilité de l'installation de ce système sous une serre pour couvrir partiellement les charges énergétiques.

Abstract

Throughout history, urban agriculture has gained attention as a means of addressing food security and disruptions to global food supply chains while allowing the production of local vegetables. Climate change and global warming, mostly caused by greenhouse gases, highlight the importance of heating and cooling urban greenhouses with sustainable methods, for example with ground source heat pump systems. Slinky coil horizontal ground heat exchangers (HGHEs) are a cost-effective alternative for keeping ground source heat pump installation costs affordable to urban greenhouses, but trench space requirements can be an issue. Thus, the objective of this study was to assess the potential of HGHEs to heat and cool urban greenhouses while installing such a system under the greenhouse to save space. Using climate normals, an energy consumption profile for a greenhouse being designed in La Pocatière (Québec, Canada) was estimated and the in-situ ground thermal properties were assessed. Then numerical simulations were made with the finite-element simulator FEFLOW to evaluate the performance of HGHEs installed under the greenhouse. The effect of the greenhouse maintaining a constant temperature above the HGHE was considered to determine the heating and cooling loads that can be provided with HGHEs only covering the greenhouse surface. The simulations implied four scenarios compared with a base case. The study confirms that a minimum of 7.1% of the total heating load and 26.5% of the cooling loads of a small greenhouse (133 m^2 area) can be covered by an HGHE at a 1.5 m depth when the greenhouse is not built above the HGHE system. In contrast, when the same HGHE is installed under a greenhouse with a constant temperature of 21°C, the heating loads covered increase to 22.8% and the cooling covered loads decrease to 24.2%. A sensitivity analysis indicates that the greenhouse's constant temperature reduces the system's dependence on surface temperature fluctuations for both heating and cooling.

Résumé

Tout au long de l'histoire, l'agriculture urbaine a attiré l'attention en tant que moyen de répondre à la sécurité alimentaire et aux perturbations des chaînes d'approvisionnement alimentaire mondiales, tout en permettant la production de légumes locaux. Les changements climatiques et le réchauffement de la planète étant principalement dus aux gaz à effet de serre, il est très important de chauffer et de refroidir les serres urbaines tout en respectant la durabilité environnementale, en utilisant des technologies telles que les systèmes de pompes à chaleur géothermiques. Les échangeurs de chaleur souterrains horizontaux (ÉCGHs) à serpentin constituent une méthode rentable pour réduire les coûts d'installation de ces systèmes, ce qui les rend plus abordables que les systèmes conventionnels de pompes à chaleur géothermiques pour les serres urbaines. L'objectif de cette étude est d'évaluer le potentiel des échangeurs de chaleur horizontaux dans le chauffage et le refroidissement des serres urbaines et d'explorer la possibilité d'installer ce système sous la serre pour économiser de l'espace, tout en considérant une méthode rentable. En utilisant les normales climatiques, un profil de consommation d'énergie pour une serre en cours de conception à La Pocatière (Québec, Canada) et des évaluations in situ des propriétés thermiques du sol, des simulations numériques réalisées avec le simulateur à éléments finis FEFLOW v. 7.5 ont visé à déterminer dans quelle mesure les charges de chauffage et de refroidissement peuvent être couvertes si les systèmes de chauffage et de refroidissement sont uniquement installés sous la serre. L'effet de la serre qui maintient une température constante au-dessus du système de chauffage et de refroidissement a été pris en compte. Les simulations ont donné lieu à quatre scénarios comparés à un cas de base. L'étude confirme qu'un minimum de 7.1 % et de 26.5 % des charges totales de chauffage et de refroidissement d'une petite serre (133 m^2 de surface) peuvent être couvert par un chauffe-eau à une profondeur de 1.5 m lorsqu'il n'y a pas de serre au-dessus. En revanche, lorsque le même chauffe-eau est installé sous une serre à température constante de 21 °C, les charges de chauffage couvertes passent à 22.8 % et les charges de refroidissement couvertes diminuent à 24.2 %. L'analyse de sensibilité indique que la température constante de la serre réduit la dépendance du système à l'égard des fluctuations de la température de surface pour le chauffage et le refroidissement, même si le refroidissement est moins efficace.

2.1 Introduction

Urban agriculture has been developed throughout history, particularly during times of crisis, where residents have grown fruits and vegetables in community or personal gardens to access a direct food source (McClintock, 2010). The COVID-19 pandemic is a good example of such a world crisis that triggered food insecurity in many cities (Gundersen et al., 2021). Urban agriculture has emerged as a way to address these issues and allow production of fresh and local goods to avoid disruptions to global food supply chains. While this reduces food insecurities and increases social well-being, there are high costs and constraints (Mok et al., 2014). A citizen's socioeconomic status and access to land on which personal gardening is possible are two important constraints that make personal gardens only attainable for a certain amount of the population (Schupp, 2017). Therefore, social enterprises, community-based organizations and municipal initiatives play a key role in improving food security in underprivileged districts (Bach & McClintock, 2021). Development of social economy initiatives can contribute to food security in neighborhoods.

Various types of urban agriculture can be developed in order to benefit a community. The following are common types: backyard gardens, street landscaping, tactical gardens, greenhouses, forest gardening, rooftop gardens, green walls, vertical farms, animal husbandry, urban beekeeping and aquaponics (Spacey, 2017). Costs and constraints vary greatly with every type of chosen agriculture which can be residential, commercial, or communal.

Greenhouses are becoming increasingly popular for agriculture due to their high output, which is 10-20 times greater per unit area than outdoor production (Ahamed et al., 2019). However, maintaining a controlled temperature in these environments requires significant energy costs. To avoid damaging the plants, the temperature must remain within a specific range, with maximum variation within 5-7 °C (Mohamed, 2003). As a result, the majority of the energy consumed by greenhouses goes toward heating, with the rest being used for electrical apparatus such as lighting and irrigation (Zhang et al., 2020). This presents a significant challenge for greenhouse growers in cold regions who must find affordable solutions.

It is widely known that climate change and global warming are due to greenhouse gases, mostly of anthropogenic nature. Reduction of CO_2 emissions is a major concern (IPCC, 2014). Hence, transition toward sustainable energies is of great importance to succeed in decarbonization of the energy sector. It is therefore important to sustainably heat and cool urban greenhouses considering; 1) renewable energy sources, which have a lower carbon footprint compared to traditional fossil fuels; 2) energy dependence, to reduce operator vulnerability to cost fluctuations and energy supply disruptions (De Rosa et al., 2022); and 3) public perceptions, since using renewable energies can enhance the public image and reputation of environmentally responsible food producers.

Ground source heat pump systems (GSHPs) account for the majority of geothermal applications in direct use, with 71.6% of the installed capacity and 59.2% of annual energy consumption reported in 2020 (Lund et al., 2020). However, these systems have a higher installation cost compared to traditional heating systems, such as furnaces, boilers, heat pumps and space heaters (Farabi-Asl et al., 2018). There are three main types of geothermal heat pump systems: groundwater, surface water and ground-coupled heat pumps. Open-loop systems in aquifers and surface water circulate water from an aquifer, lake, or pond, but this method is less common as it requires a nearby water source. Ground-coupled heat pumps have closed-loop heat exchangers commonly installed in boreholes or trenches. Vertical systems rely on a constant ground temperature at a certain depth and require drilling to insert pipes into the ground, which is costly but does provide a space-efficient option. Horizontal systems consist of pipes buried in trenches at a depth of about 1 to 2 m, where water or a mixture of water and antifreeze circulates (Chiasson, 2016). Since the trenches are rather shallow, these systems are subject to atmospheric temperature fluctuations that diffuse into the ground.

Slinky coil horizontal ground heat exchangers (HGHEs) can be a cost-effective method for reducing installation costs of GSHP systems that are installed with a backhoe loader for shallow excavations instead of a drill rig for boreholes. However, this type of HGHE requires a sufficient amount of space to bury the heat exchange pipes, which makes it harder to install in locations with limited space. In this case, the geothermal system can be combined 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, 2013; Léveillée-Dallaire et al., 2022). Greenhouses can be compatible with such hybrid geothermal systems relying on HGHEs, since the floor is often composed of unconsolidated soils, which facilitates installation.

Using an analytical approach, Morshed et al. (2022) showed that earth-to-air heat exchangers can help reduce the energy consumption and costs for building heating and cooling. Their work was for tubular heat exchangers to heat an agricultural greenhouse located in a Mediterranean climate in the coastal area of West Syria. Depending on the length of the tubes, an energy output of 35% to 60% of the greenhouse total energy consumption was obtained.

Chiriboga et al. (2021) explored the possibility of using low enthalpy geothermal systems to heat a 470 m^2 greenhouse located in the Andean mountains with a setpoint of 15 °C at night and 30 °C during the day, comparing measured and simulated inside air temperatures. The system was found to be capable of delivering a thermal power output of 29.56 and 65.76 kW for heating and cooling, respectively. The calculated capacity factor implies a required lifetime of about 12-14 years to reach an acceptable levelized cost of energy (LCOE).

Hou et al. (2022) made a comprehensive review of HGEs, classifying systems into 3 types, namely the spiral coil, slinky-coil and linear U, which were shown to be more economical than vertical ground heat exchangers when there is enough land available. Their review brings together analytical, numerical, and experimental models to simulate HGHEs. They concluded that the buried depth does not play an important role relative to other system parameters. Ground heat exchanger (GHE) parameters such as center-to-center pipe distance, pitch, and pipe layout have a substantial impact on the system performance and adjustment is necessary to achieve optimal design. Helical-coil distribution layouts provide additional optimal thermal performance while being pricier.

Chong et al. (2013) developed a slinky HGHE numerical model using the Fluent software, testing 5 different pitch configurations of 0.25 m, 0.5 m, 1.0 m, 2.0 m and 3.0 m with diameters of 0.8 m, 1 m and 1.2 m. The pitch configuration refers to how the coils are laid out in terms of the spacing and depth between each coil and the orientation of the coil pattern. The specific pitch configuration can vary depending on factors such as soil conditions, available space, and desired heat transfer efficiency. Results suggested that reducing the coil pitch could improve the overall system performance, reduce the system thermal resistivity by 20%, and decrease the overall excavation costs by 15%. They also concluded that local soil thermal and hydraulic properties highly influenced system performance.

Tang et al. (2020) modeled a numerical slinky-coil HGHE involving atmosphere-soil-HGHE interaction, validating the model with a local temperature probe and comparing measured to simulated temperatures. Their work demonstrated that there is no significant difference in the outlet fluid temperature when the depth of the HGHE is increased from 0.5 m to 1 m. The study points out that numerical simulations are important in the case of atmosphere-soil-HGHE interaction.

Fujii et al. (2012) numerically modeled a slinky HGHE and the surrounding soil using the finite-element simulator FEFLOW (Diersch, 2013). A comparison between the numerical model and a thermal response test (TRT) experiment on the HGHE was made to validate the simulation approach. The results revealed that their thin plate model can be used to simulate HGHEs for pipe and fluid thermal conductivity in the range of 0.025 $Wm^{-1} K^{-1}$ to 0.045 $W m^{-1} K^{-1}$. This present study used the same approach as that developed by Fujii et al. (2012). The heat exchange rate per unit length of the straight horizontal heat exchange pipes is significantly lower than that obtained with a vertical ground heat exchanger because temperature in the shallow ground shows seasonal variations and dry soil near land surface has a relatively low thermal conductivity. Using slinky-coil heat exchange pipes instead of straight pipes is therefore a good alternative to collect more energy per unit trench length, which can facilitate the development of such systems, even in cases of limited land availability (Fujii et al., 2012).

This work provides a comprehensive assessment of the heating and cooling capacity of HGHEs in the context of urban greenhouse systems. By considering different scenarios and incorporating a sensitivity analysis, we offer a deeper understanding of the different interactions between the building and the HGHE. The work achieved also explored the use of HGHEs for greenhouses, for which limited research has been made. The practical aspect of this study is also noteworthy, providing insights for practitioners aiming to improve sustainability of heating and cooling. Our work finally showed that a finite-element simulator such as FEFLOW (Diersch, 2013) could be used in such practical cases for HGHE under a greenhouse, which is not covered by the software.

In urban areas, there is little land space to install HGHEs. It therefore seems important to know if HGHEs installed under the limited surface of a building such as a greenhouse can cover significant heating and cooling loads. We hypothesize that an HGHE covering a limited area located under a greenhouse can be attractive to users because of reduced installation costs but would likely not cover the full heating or cooling loads of the greenhouse when installed in a continental humid climate like that of Quebec, Canada, where the heating demand is high in winter. Thus, numerical simulations were made following the work done by Fujii et al. (2012; 2013) to evaluate the percentage of the greenhouse heating and cooling loads that can be covered with an HGHE of limited surface area installed under the greenhouse.

Until today, few studies have been made for HGHEs located below a building like a greenhouse, specifically in urban settings even though it is a way of addressing both CO_2 emissions and food insecurity in cities. Hence, it is important to assess the effect of such a system considering local ground thermal properties, ambient and greenhouse air temperature and building energy consumption. A field site was thus chosen and characterized for this study aiming to provide information and guidance to integrate HGHE in greenhouses located in a cold continental humid climate like that of Quebec. The objective of this study was to assess an HGHE's potential to heat and cool urban greenhouses when installing this system under the greenhouse to save space and cost.

The Cégep de La Pocatière is planning to build an enclosed greenhouse and complementary research buildings (Figure 2.1). The project aims to demonstrate that such a research complex can be air-conditioned mainly with renewable energy sources such as geothermal heat pump systems. A hybrid heating system is envisioned whereby an HGHE would be installed below the greenhouse to minimize installation costs knowing that the system can only fulfill part of the heating and cooling needs. Auxiliary heating and cooling sources would be needed to cover the full heating and cooling loads of the greenhouse. This site was consequently chosen to conduct the study although the conclusions can provide guidelines for other greenhouses in similar settings.

2.2 Background information

2.2.1 Previous site studies

The study takes place in the province of Québec, Canada, more precisely in the village of La Pocatière (Figure 2.1). The planned greenhouse, currently in the design phase, has an expected dimension of 14.6 m × 9.1 m, for a total of nearly 133 m^2 with a height of around 6.1 m. Work was conducted to evaluate the heating and cooling energy consumption of the greenhouse and in situ subsurface characterization was completed to evaluate the feasibility of a shallow geothermal systems.

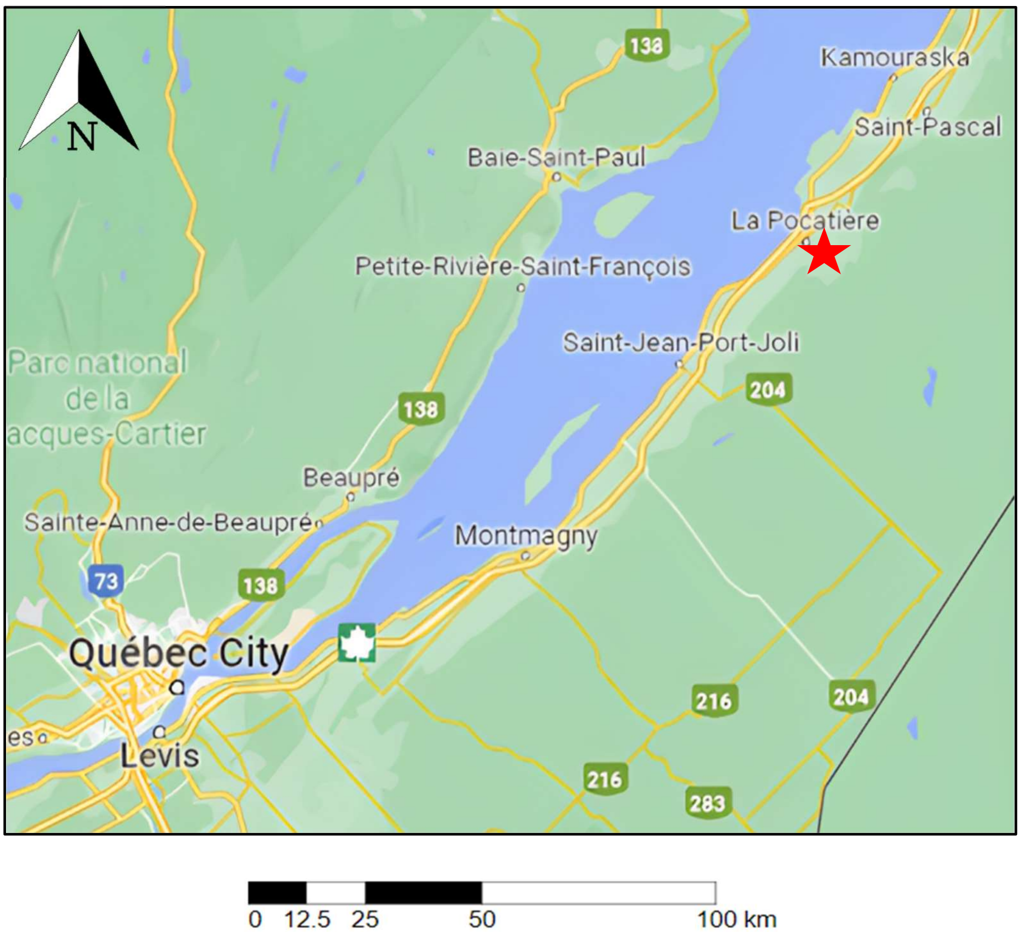

Figure 2.1. La Pocatière greenhouse location shown by a red star.

An energy analysis study in a controlled environment was previously conducted by Enerprox Inc. to define the energy consumption profile for three scenarios: an open greenhouse, a semi-open greenhouse, and a closed greenhouse (Enerprox, 2022). The study aimed to maintain vapor pressure deficit conditions to optimize plant growth conditions, control the airflow and CO_2 injection, and to optimize the energy use. The study resulted in an energy consumption profile for heating and cooling considering dehumidification for the open and closed greenhouse. The consumption profile gives the average and maximum monthly energy to heat and cool the building. The HGHE under the greenhouse aims to cover base loads, and the average monthly consumption profile was used as input for our simulations. The profile for a closed greenhouse was chosen for our study, assuming a 21 °C constant temperature inside the greenhouse (Figure 2.2). The load profile displays both heating and cooling demand; therefore, only the higher consumption is considered to determine whether the month belongs to a heating or cooling period. Heating dominated periods are for the months of October to February while cooling dominated periods are for the months of March to September.

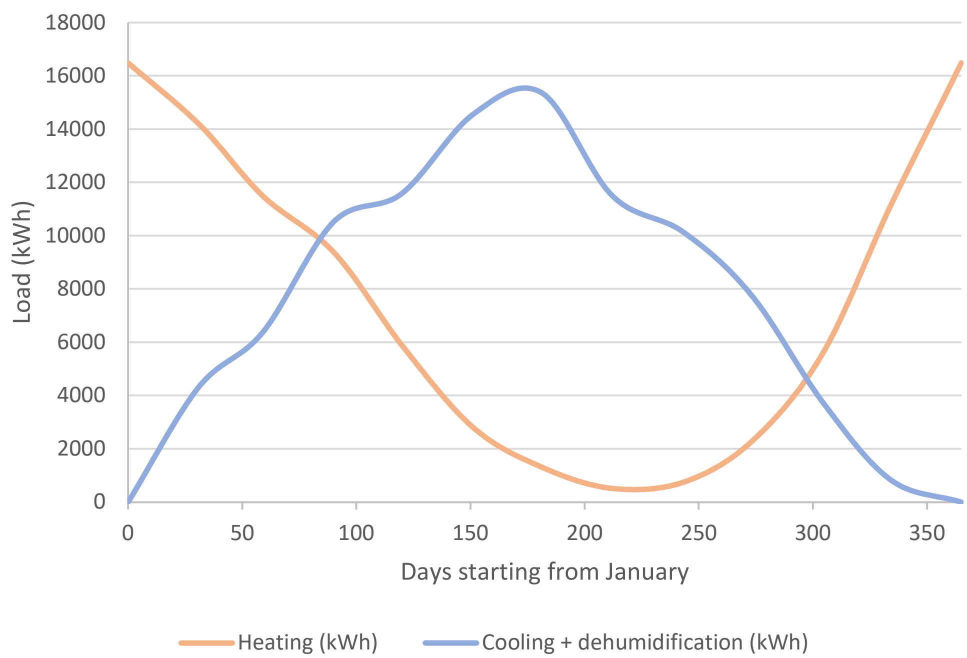

Figure 2.2. Monthly heating and cooling load profiles for the greenhouse in La Pocatière.

The consulting company Géotherma Solutions Inc. was mandated for a pre-feasibility study to design a shallow geothermal heat exchanger system for the greenhouse. The study included field and laboratory work to determine the thermal conductivity and thermal diffusivity of the soil as well as sizing calculations. Three soil samples were subject to laboratory needle probe analysis and two oscillatory thermal response tests (O-TRT) were made (Langevin et al., 2023).

Surface deposits are clayey silt and fine deep-water glaciomarine sediments (Géotherma Solutions Inc., 2022). The K2DPro—Decagon needle probe was used for soil thermal property analyses in saturated and in situ conditions using the infinite line source equation in a transitional regime. Measurements made on samples do not represent the entire field area since only small samples were analyzed in the laboratory. The SH-1 needle was used to define both the thermal conductivity and heat capacity. Oscillatory and constant heat injection TRT tests better evaluate in situ soil conditions but take more time to complete. The OTRT test allowed us to determine the soil heat capacity, which can't be done with a constant heat injection TRT test. In situ OTRTs were made using a 3 m long heating cable and 5 temperature sensors.

The average thermal conductivity and heat capacity of the samples analyzed in the laboratory were between 1.45 – 1.50 W m^{-1} K^{-1} and 2.85 – 4.05 MJ m^{-3} K^{-1}, respectively. OTRT test results indicated an in-situ ground thermal conductivity between 1.07 W m^{-1} K^{-1} and 1.60 W m^{-1} K^{-1} and a ground heat capacity varying between 1.78 - 2.62 MJ m^{-3} K^{-1}. Therefore, a thermal conductivity of 1.41 W m^{-1} K^{-1} and a heat capacity of 2.86 MJ m^{-3} K^{-1} was chosen for the ground in the numerical simulations of this study, considering the average of the various measurements (Table 2.1; Giordano et al., 2022).

Table 2.1. Ground thermal properties.

	Samples (*Geotherma Solutions*)	**OTRT (*Geotherma Solutions*)**	**Chosen value**
Ground heat capacity (MJ m^{-3} K^{-1})	2.85 - 4.05	1.78 - 2.62	2.86
Ground thermal conductivity (W m^{-1} K^{-1})	1.45 - 1.50	1.07 - 1.60	1.41

2.2.2 Ground temperature

Ground surface temperature was defined using Equation 2.1 aiming to predict the ground temperature from historic air temperature (Ouzzane et al., 2015) :

$$T_{\mathrm{g}} = 17.898 + 0.951 \times T_{\mathrm{amb}} \tag{2.1}$$

where T_{g} and T_{amb} are the ground and ambient air temperature in Kelvin, respectively. This empirical relationship was developed considering the effects of the ambient temperature, the wind velocity, and the solar radiation. The formula gives an estimate of the ground temperature with a simple approximation in Canada. Values for T_{amb} were taken from the monthly average temperature of the climate normal for La Pocatière (Government of Canada, n.d.). During December, January, and February the ground is covered by snow, which acts as an insulation layer for the ground. The ground temperature at the surface during this period was therefore considered to be -1 °C (Langevin, 2022), providing the resulting ground surface temperature profile given in Table 2.2.

Table 2.2. Ground surface temperature profile.

Months	**Ambient temperature T_{amb} (°C)**	**Calculated ground temperature T_{g} (°C)**	**Ground temperature considering snow insulation T_{g} (°C)**
January	-11.6	-6.5	-1.0
February	-9.4	-4.4	-1.0
March	-4.0	0.7	0.7
April	3.7	8.0	8.0
May	11.2	15.2	15.2
June	15.9	19.6	19.6
July	18.8	22.4	22.4
August	18.5	22.1	22.1
September	13.9	17.7	17.7

October	6.9	11.1	11.1
November	0.5	5.0	5.0
December	-7.2	-2.3	-1.0

Due to a lack of information, undisturbed ground temperature is not known for the greenhouse site. The empirical correlation proposed by Ouzzane was therefore used to calculate the undisturbed ground temperature at a greater depth (~20 m) considering the average annual ambient air temperature. This revealed an undisturbed ground temperature of 9.1 °C at 20 m depth. This result was compared with measurements taken in the surrounding area for validation. The average undisturbed ground temperature profile evaluated for six (6) locations in Québec City, which is 120 km from La Pocatière, was 9.2 °C (Léveillée-Dallaire et al., 2020), and that calculated with Ouzzane's empirical equation for the same location is 9.1 °C. Therefore, it seems reasonable to use an undisturbed ground temperature of 9.1 °C at a depth of 20 m in the numerical simulations for this study of a greenhouse in La Pocatière.

2.3 Methodology

2.3.1 FEFLOW HGHE model

2.3.1.1 Conceptual model and governing equations

A simplified sketch of an HGHE is presented in Figure 2.3, where excavations with slinky coil pipes are visible. The simulations consider varying depths for the slinky coil layer at 1 m, 1.5 m and 2 m below the ground surface.

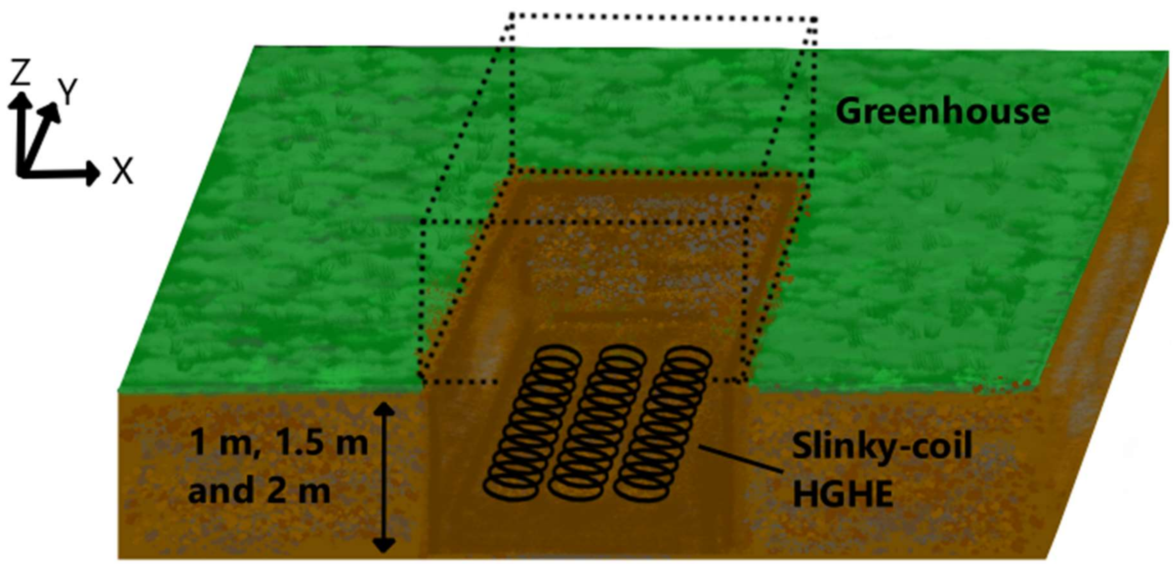

Figure 2.3. Conceptual model of the study site.

The simulations of the HGHE operation were carried out using the software FEFLOW (Diersch, 2013), based on the work by Fujii et al. (2012, 2013). The following equations govern mass and heat transport in the ground, represented by the fluid mass conservation equation (2.2), followed by the momentum conservation equation (2.3) and the energy conservation equation (2.4):

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha) + \frac{\partial}{\partial x_i}(\varepsilon_\alpha \rho^\alpha v_\mathrm{i}^\alpha) = \varepsilon_\alpha \rho^\alpha Q_\rho^\alpha \quad (2.2)$$

$$v_\mathrm{i}^\alpha + \frac{\mathbf{k}_\mathrm{ij}^\alpha}{\varepsilon_\alpha \mu_\alpha}\left(\frac{\partial p^\alpha}{\partial x_\mathrm{j}} - \rho^\alpha g_\mathrm{j}\right) = 0 \quad (2.3)$$

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha E^\alpha) + \frac{\partial}{\partial x_\mathrm{i}}(\varepsilon_\alpha \rho^\alpha v_i^\alpha E^\alpha) + \frac{\partial}{\partial x_\mathrm{i}}(j_{\mathrm{i}T}^\alpha) = \varepsilon_\alpha \rho^\alpha Q_\mathrm{T}^\alpha \quad (2.4)$$

where ε is the porosity (-), ρ is the fluid density (kg m^{-3}), α is the ground thermal diffusivity (m^2 s^{-1}), v_i is the vector of pore velocity (m s^{-1}), Q_ρ is the fluid mass sink/source (s^{-1}), Q_T is the source of heat (kg m^{-1} s^{-3}), $\mathbf{k}_{ij}$ is the permeability tensor (m^2), μ is the dynamic viscosity of gas (kg m^{-1} s^{-1}), p is the fluid pressure (Pa), j_{iT}^α is Fourier's heat flux vector (kg s^{-3}), g_j is the gravitational vector (m s^{-2}), x_i are the Cartesian coordinates (m) and E is the internal (thermal) energy density (m^2 s^{-2}).

2.3.1.2 The numerical model

The numerical model is presented in Figure 2.4, where the green area consists of the grid elements representing the slinky coil HGHE. The inlet and outlet, where the heat pump leaving fluid temperature (LFT) and entering fluid temperature (EFT) are respectively calculated, are shown by the red and yellow dots.

Since slinky coil HGHE modelling can require heavy computing time, Fujii et al. (2012, 2013) proposed to model a thin flat plate instead of fully discretizing the HGHE, which results in faster computation time and similar results to those obtained with fully discretized models. Although it is possible to reproduce the coil shape in a fully discretized model, it is not practical from a computational time perspective. The resulting thin plate model is composed of three parts: the flow path, the pipes, and the ground. The HGHE is composed of the flow path and the pipes, but those two components have different thermal and hydraulic properties. The thin plate model is shown in Figure 2.5, as an excerpt (the small green box) from the 3D model shown in Figure 2.4. It is assumed to have a length equal to the HGHE trench length and a width equal to the slinky coil inner diameter. In order to match the arrival time of the heat transfer medium from the heat exchanger inlet to the heat exchanger outlet between the numerical model and the field test results, the volume of the thin plate is made equal to the volume of the flow channel in the slinky coil HGHE (Figures 2.4, 2.5). The thickness of the flow path in the thin plate on the z-axis is calculated using Equation 2.5 (Fujii et al., 2012):

$$z = \left(\frac{d_{inner}}{2}\right)^2 \times \pi \times \frac{L}{(X \times W)} \tag{2.5}$$

where z, d_{inner}, L, X and W are the total thickness of the grid corresponding to the flow path (m), inner diameter of the polyethylene pipe (m), total length of the buried slinky coil HGHE (m), length of the trench in which the slinky coil HGHE is buried (m) and width of the trench where the slinky coil HGHE is buried (m).

The flow path is therefore composed of three layers, with one layer above and below representing the pipe walls (Figure 2.5). The gray part represents the pipe walls, while the blue part represents the flow path where the fluid flows. The flow path has a high porosity and high hydraulic conductivity while the rest of the model has very low porosity and hydraulic conductivity. This makes water flow in the pipes from the inlet to the outlet. Specific values for the HGHE thermal conductivity and heat capacity, for both the polyethylene pipe and the flow path, were previously determined by calibration to reproduce temperature observed during field tests. The model was validated using the TRT results and a long-term air-conditioning test, which were conducted while varying the operating conditions (Fujii et al., 2012, 2013).

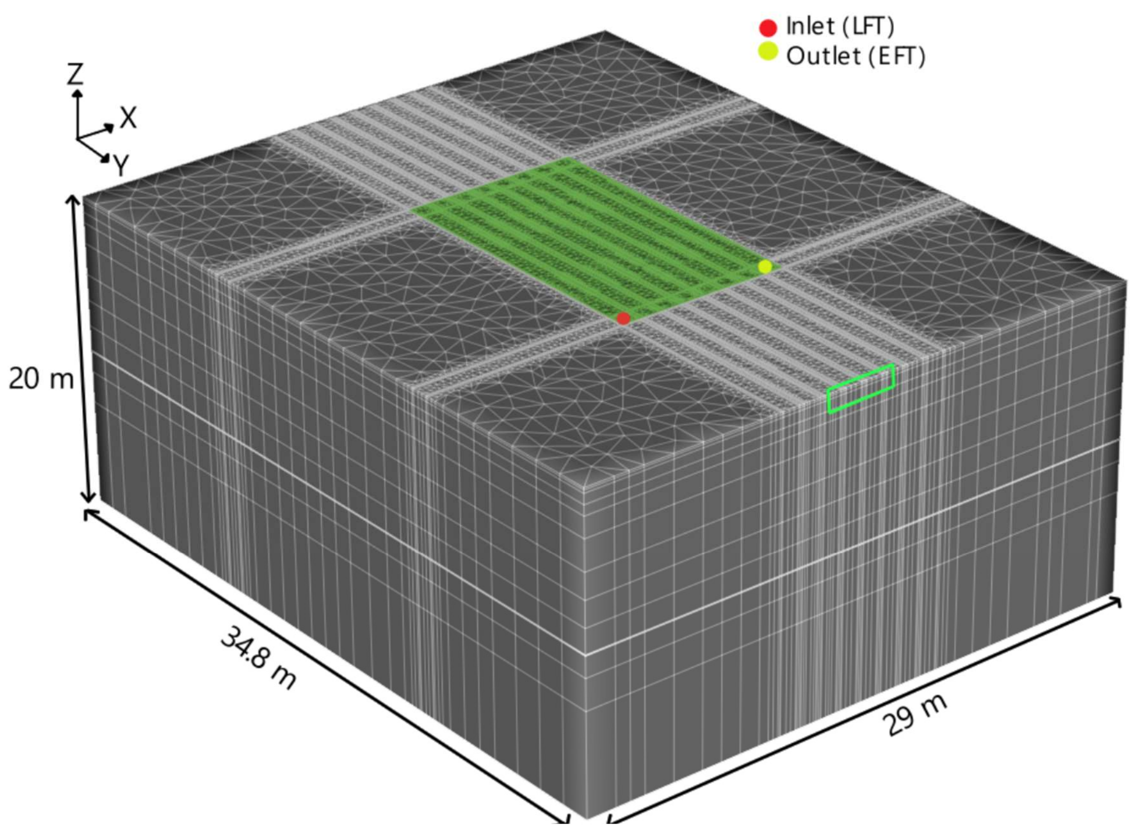

Figure 2.4. 3D view of the numerical model showing the HGHE (green filled area).

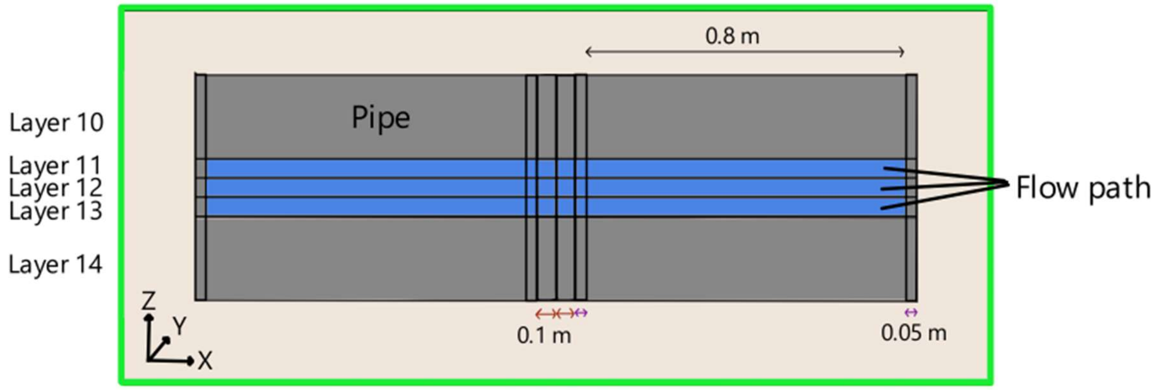

Figure 2.5. Cross-section of the thin plate model.

2.3.1.3 Domain Discretization

The mesh made of the triangular prismatic elements was defined considering Delaunay Forces (Diersch, 2013). The grid surrounding the HGHE was refined while the grid close to the outer boundaries was coarsened to reduce simulation time. The model enclosed a total of 40 800 elements and 20 544 nodes. Vertical slices were positioned at a distance ranging between 0.02 and 5 m, depending on the location of the slice. The first slice is set at 0 m and the next slices are located at a 0.02 m, 0.04 m, and 0.08 m. This principle was also applied for slices surrounding the HGHE. In total, there are 22 slices. Numerical errors were minimized by respecting the Peclet (Pe) and Courant (Co) criteria, given in Equations 2.6 and 2.7, respectively:

$$Pe = \frac{v\Delta X}{\alpha} \leq 2 \tag{2.6}$$

$$Co = \frac{v\Delta t}{\Delta X} \leq \frac{Pe}{2} \tag{2.7}$$

with Pe and Co equal to a maximum of 0.0949 and 7.436×10^{-5}, respectively. Those dimensionless numbers were computed by the FEFLOW software using the mesh, flow velocities, diffusivity coefficient, and time steps. The outer bottom and lateral boundaries of the model are located 10 m from the HGHE to minimize any influence from conditions imposed at these boundaries. The size of the model is 34.8 m in the y-axis, 29 m in the x-axis and 20 m in the z-axis. The size of the HGHE is 14.6 m by 9.1 m and is made of 8 trenches of slinky coils. There is a 0.2 m distance between every trench, which is composed of a fluid path (0.8 m) and pipes (2 × 0.05 m).

2.3.1.4 HGHE Operating Parameters and Model Properties

The key operating parameters and model properties are shown in Table 2.3., The model is based on ground heat exchangers with a winding pitch of 0.6 m, an inner diameter of 0.8 m, and a pipe thermal conductivity of 0.34 W m^{-1} K^{-1}. The HGHE inner and outer pipe diameter is 0.024 m and 0.034 m, respectively. There is injection of fluid at the inlet and pumping at the outlet (Figure 2.7). The flow rate is set at 0.0002 m^3 s^{-1}. To make sure that the flow is turbulent (Re >2300), the flow rate chosen for the fluid inside the pipe was the same as that used by Fujii's et al. (2012, 2013), since their model was validated using the results of a TRT on a horizontal HGH and a long-term air-conditioning (A/C) test. The percentage of propylene glycol was set at 20%, with a freezing point of -7.1 °C and a heat capacity of 4.02 MJ m^{-1} K^{-1}.

Table 2.3. Operating parameters.

HGHE parameters	
HGHE pitch (m)	0.6
HGHE slinky coil diameter (m)	0.8
HGHE pipe thermal conductivity (W m^{-1} K^{-1})	0.34
Inner pipe diameter (m)	0.024
Outer pipe diameter (m)	0.034
Flow rate (m d^{-1})	17
Fluid composition (% of propylene glycol)	20
Fluid freezing point (°C)	-7.1
Fluid heat capacity (MJ m^{-1} K^{-1})	4.02

The flow path has a hydraulic conductivity of 0.001 m s^{-1} and a porosity of 1 (Fujii et al., 2012). The pipes and the ground have a hydraulic conductivity of 1 x 10^{-15} m s^{-1} and a porosity of 0.0001. These values are set to prevent water flow from leaking outside the flow path. According to Fujii et al. (2012, 2013), the heat transfer medium (flow path) has a heat capacity of 3.800 MJ m^{-3} K^{-1}. Both the flow path and the pipes have a thermal conductivity of 0.027 W m^{-1} K^{-1}. This last value was determined by calibration to reproduce the TRTs made on HGHEs. The ground thermal properties were set according to Géotherma Solutions Inc. study results (Géotherma Solutions Inc., 2022), with a ground thermal conductivity of 1.414 W m^{-1} K^{-1} and a ground heat capacity of 2.86 MJ m^{-3} K^{-1}. This last value is also applied for the pipes (layers 10 and 14, Figure 2.5) since the soil element accounts for a large proportion of the polyethylene pipe element (Table 2.4).

Table 2.4. Model properties

		Flow path	Pipes	Ground
Hydraulic properties	Hydraulic conductivity (m s^{-1})	0.001	1.00E-15	1.00E-15
	Porosity	1	0.0001	0.0001
Thermal properties	Heat capacity (MJ m^{-3} K^{-1})	3.800	2.86	2.86
	Thermal conductivity (W m^{-1} K^{-1})	0.027	0.027	1.414

The simulations aim to determine how much of the heating and cooling loads can be covered if HGHEs are only installed under the greenhouse and to assess the effect of the constant surface temperature on its performance. The HGHE would cover the base loads since we assume their surface area would be too small to cover the entire building loads.

2.3.1.5 Model Boundary Conditions

To assess the effect of the greenhouse and its constant temperature at the ground surface on the top of the HGHE, numerical simulations were completed for cases with different boundary conditions representing the presence or absence of the greenhouse above the HGHE.

Outer fluid flow boundaries were treated as no-flow Neumann boundaries. The nodes surrounding the HGHE were also defined as no-flow boundaries to prevent the flow path from leaking. Rain infiltration was considered negligible. The excavations realized during the TRT on the site showed that the groundwater level is below 1.5 m and the soil was assumed to be unsaturated in the shallow ground.

Peripheral heat transfer boundary conditions were defined as adiabatic (Figure 2.6). Surface temperature varies since some scenarios include a greenhouse above the HGHE and some do not. The surface covered by the greenhouse was set to have a constant temperature of 21 °C for the simulations, which comes from the Enerprox Inc. study (Enerprox, 2022). Otherwise, the ground surface temperature profile (Table 2.2) was used for the top boundary and an undisturbed ground temperature of 9.1 °C was used for the bottom boundary, at a depth of 20 m (Figure 2.6). A given temperature was set at the inlet so that the LFT is known (Figure 2.7), and the EFT was calculated during the simulations. The LFT was assumed to be -4 °C for heating and 34 °C for cooling simulations. However, it should be noted that the chosen LFT values do not accurately represent the hourly energy demand, as it would normally be fluctuating through the day.

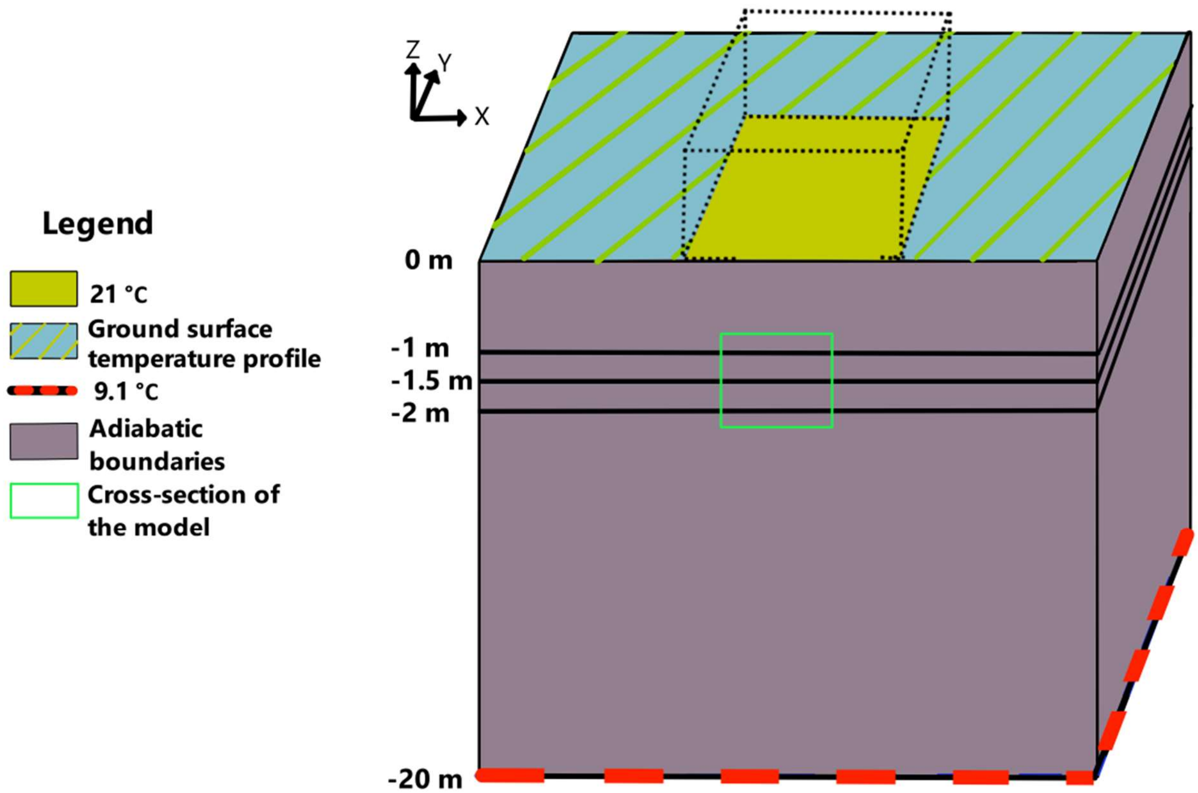

Figure 2.6. Model heat transfer boundary conditions for simulations at different depths. A cross-section is shown in Figure 2.7.

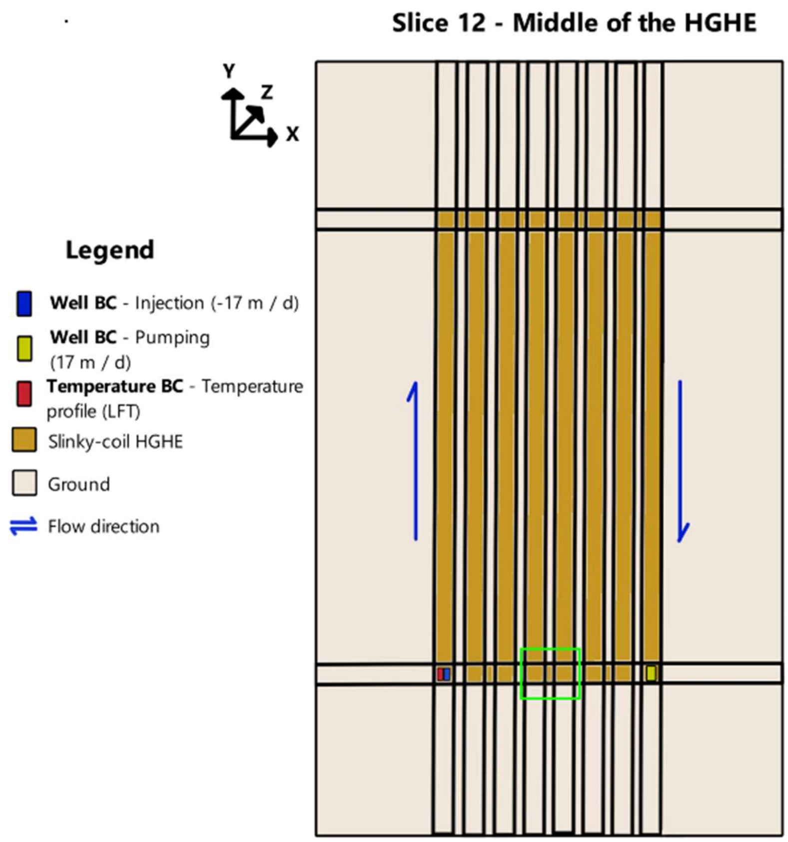

Figure 2.7 The middle slice of the HGHE model (Figure 2.5) and the key internal conditions used to simulate HGHEs.

2.3.1.6 Initial Conditions and Simulation Time

Initial temperature and flow conditions prior to the HGHE simulations were simulated for a year without any thermal extraction or injection from the HGHE. This means that the HGHE simulations start at the same time as the heat pump. In cases where the greenhouse is located above the HGHE, the constant temperature inside the greenhouse (21 °C) is taken into consideration for the initial temperature simulation.

The HGHE simulations were run for 5 years, from day 0 to day 1825. The initial time-step length was set to 0.001 days. To ensure optimal results, the minimum time-step size is unrestricted, while the maximum time-step size is set to 5 days. The decision to simulate the model for 5 years allows us to assess the system performance on a long-term basis. The heat pump is assumed to be operating all year for both cooling and heating.

2.3.2 Coefficient of Performance and Load Coverage Calculations

The Coefficient of Performance (COP), which is the ratio between the heating power delivered to the building and the electrical power consumed by the heat pump depends on the EFT and on the heating temperature of the building.

A linear formula was used to calculate the COP using tables for commercial ground source heat pumps and the fluid temperature varying with time during simulations. The heating and cooling heat pump COP were calculated using Equations 2.8 and 2.9.

$$COP_{heat} = 0.0936 \times EFT + 3.944 \tag{2.8}$$

$$COP_{cool} = -0.1478 \times EFT + 11.312 \tag{2.9}$$

The electrical power consumed by the heat pump (Qc) was calculated using Equations 2.10 and 2.11, according to previous studies (Casasso & Sethi, 2014; Hein et al., 2016) :

$$Q\mathrm{c} = \frac{Qs}{COP_{\mathrm{heat}} - 1} \tag{2.10}$$

$$Q\mathrm{c} = \frac{Qs}{COP_{\mathrm{cool}} + 1} \tag{2.11}$$

where Qs is the ground load (W). Thermal power extracted or injected was calculated using Equation 2.12, which considers the LFT and the EFT, or temperature at the pipe inlet and outlet :

$$Q\mathrm{s} = m' C_p \, (LFT - EFT) \tag{2.12}$$

where m' is the mass flow rate (kg s^{-1}), C_p is the heat capacity (J kg^{-1} °C^{-1}) and T is the temperature (°C). The thermal power is monthly averaged for the simulations results. Covered building loads were then calculated by the sum of Qs and Qc in heating mode and the subtraction of the last two parameters in cooling mode. The building loads covered by the HGHE were then compared with the total building load profile (Figure 2.2).

2.3.3 Simulation Scenarios

Four scenarios were simulated and compared with the base case. In every case, the HGHE covers an area equal to the greenhouse, as shown in Figure 2.3. The cases referring to the system without a greenhouse imply that the greenhouse is not directly above the system and that it has no impact on the temperature of the soil surrounding the heat exchangers. In this case, the top boundary heat transfer condition was set with the ground surface temperature profile. Cases involving a greenhouse above the system imply that the top boundary condition for heat transfer is set to represent the greenhouse with a constant temperature of 21 °C (Figure 2.6). In the base case, there is an HGHE at a 1.5 m depth with no greenhouse above. In scenario (1), the HGHE is installed at a 1m depth under a greenhouse. In scenario (2), the HGHE is installed at a 1.5 m depth under a greenhouse. In scenario (3), the HGHE is installed at a 2 m depth under a greenhouse. In scenario (4), a double-layered HGHE is installed at a depth of 1 m and 2 m under a greenhouse. Table 2.5 lists the characteristics of each scenario. Both heating and cooling seasons were simulated.

Table 2.5. Characteristics of each scenario.

	Depth of the HGHE (m)	**Presence of greenhouse above the system**	**Ground surface temperature above the system**	**Number of HGHE layers**
Base Case	1.5	No	Ground surface temperature profile	1
Scenario 1	1	Yes	21 °C	1
Scenario 2	1.5	Yes	21 °C	1
Scenario 3	2	Yes	21 °C	1
Scenario 4	1 and 2	Yes	21 °C	2

2.3.4 Sensitivity Analysis

A sensitivity analysis was performed to assess the importance of surface temperature and soil thermal properties. The analysis was carried out using the base case and Scenario 2 numerical models, which both include a single layer 1.5 m depth HGHE. Soil thermal properties and outside temperature were varied to define their effect on the system, always with the same model. Monthly ground surface temperature was increased and decreased by 3 °C while the ground thermal conductivity and heat capacity were changed by ± 0.345 W m^{-1} K^{-1} and ± 1.086 MJ m^{-3} K^{-1}, which represents the variation of thermal conductivity and heat capacity evaluated for samples and TRTs made by Géotherma Solutions Inc. (Géotherma Solutions Inc., 2022). The greenhouse temperature (21 °C in this case) always stays the same. Varying input parameters are shown in Table 2.6.

Table 2.6. Varying input parameters for the sensitivity analysis.

	Ground surface temperature for every month (°C)	**Ground thermal conductivity (W m^{-1} K^{-1})**	**Ground heat capacity (MJ m^{-3} K^{-1})**
Base case	0	1.414	2.860
Ground surface temperature increased	+3	1.414	2.860
Ground surface temperature reduced	-3	1.414	2.860
Deteriorated ground thermal properties	0	1.069	3.946
Improved ground thermal properties	0	1.758	1.774

2.4 Results from the HGHE simulations

Results for the base case and Scenario 2 show that the constant temperature of the greenhouse above the HGHE influences the temperature in the first few meters belowground (Figure 2.8, 2.9, 2.10). Here, the constant temperature seems to mainly affect the zone directly below the greenhouse. Results will be presented for the months of February and July for both the first and fifth simulation year. February and July will be used to represent the heating and cooling seasons, respectively. Additional results representing the various numerical simulations can be found in Appendix I.

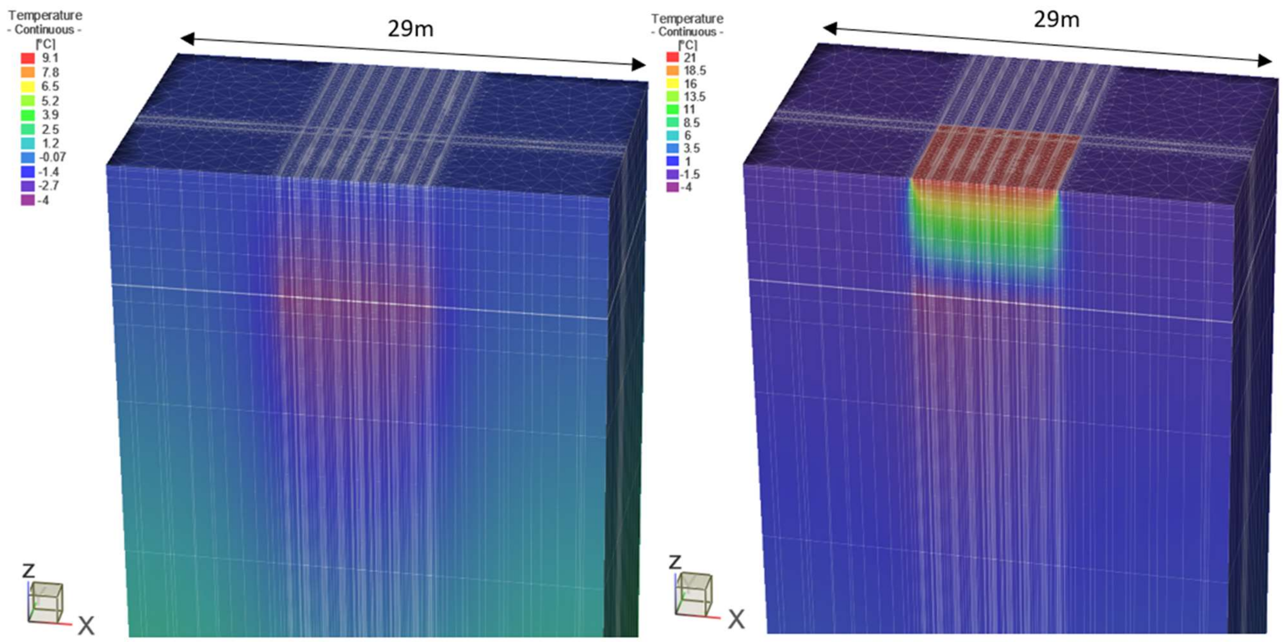

Figure 2.8. 3D perspective of the simulated temperatures in January during the fifth year. Left; base case. Right; Scenario 2.

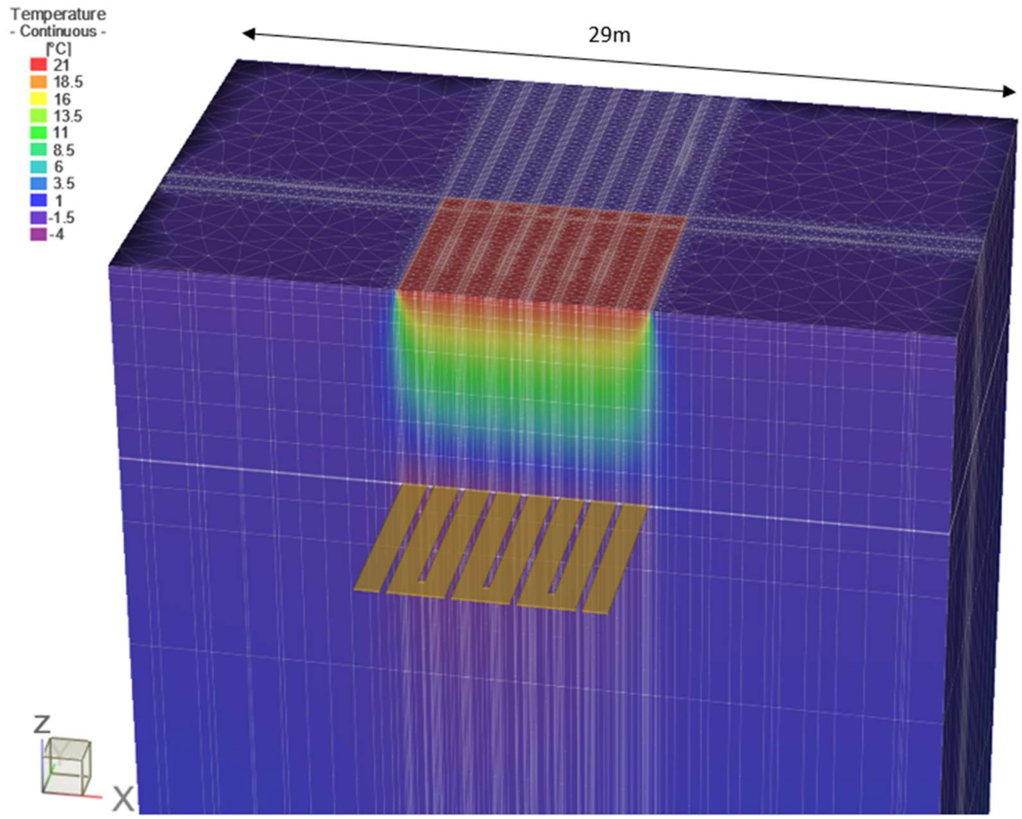

Figure 2.9. 3D perspective of simulated temperatures of the HGHE at 1.5 m (yellow) underneath a greenhouse for Scenario 2 in January during the fifth year.

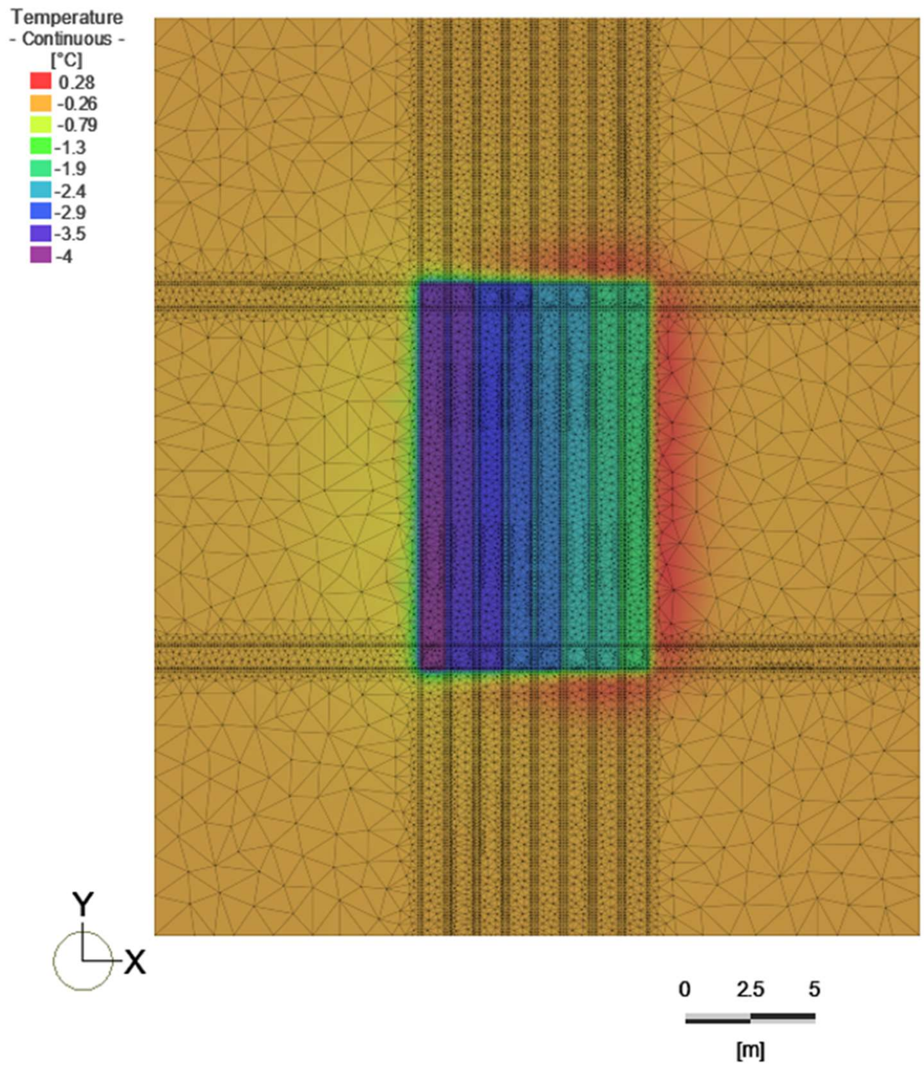

Figure 2.10. Horizontal slice view of the simulated temperatures at 1.5 m depth for Scenario 2. This slice portrays the bottom of the HGHE in January during the fifth year.

The numerical results also provide the simulated fluid temperatures at the inlet and the outlet. Figure 2.11 shows the EFT for every case, compared with the LFT. The greater the difference between EFT and LFT, the better the system's performance.

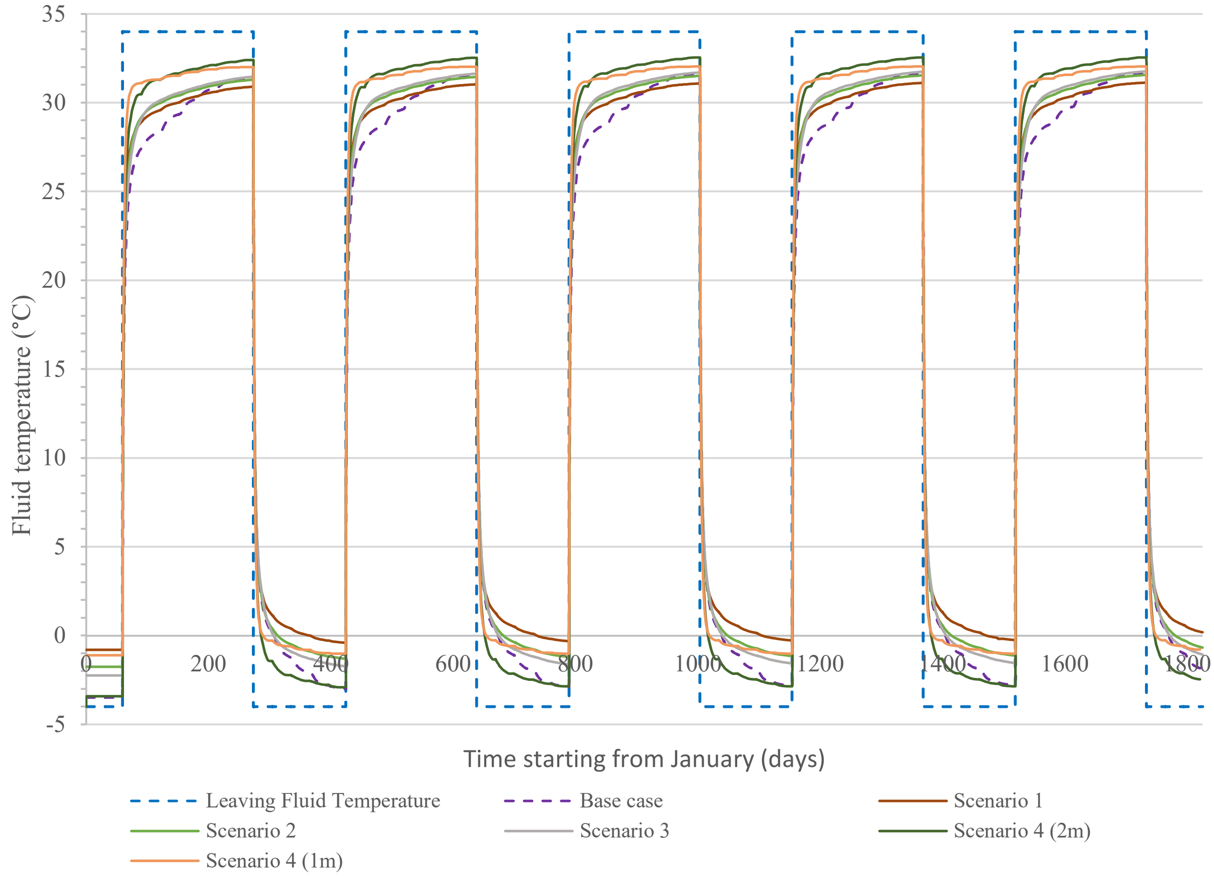

Figure 2.11. Simulated fluid temperatures for each simulation scenario. The LFT (blue line) of 34 °C is for the cooling period, while the LFT of -4 °C is for the heating period.

The highest temperature difference between LFT and EFT during the heating periods is calculated for Scenario 1, followed by Scenario 2, 4 (1 m), 3, the base case, and 4 (2 m). These intermediate results show that the greenhouse has a positive effect on the heating performance. On the other hand, the base case shows the highest temperature difference during the cooling periods, followed by Scenario 1, 2, 3, 4 (1 m), and 4 (2 m), which implies that the greenhouse has a negative effect on cooling performance. The performance of the heat exchange varies among scenarios at different times of the month. Some scenarios exhibit better performance at the beginning of the month, while others perform better toward the end. Hence, evaluating the best scenario based on fluid temperature alone is challenging. To have a better understanding of the results, fluid temperature can therefore be converted into the percentage of the total heating and cooling covered by the system (Figure 2.12).

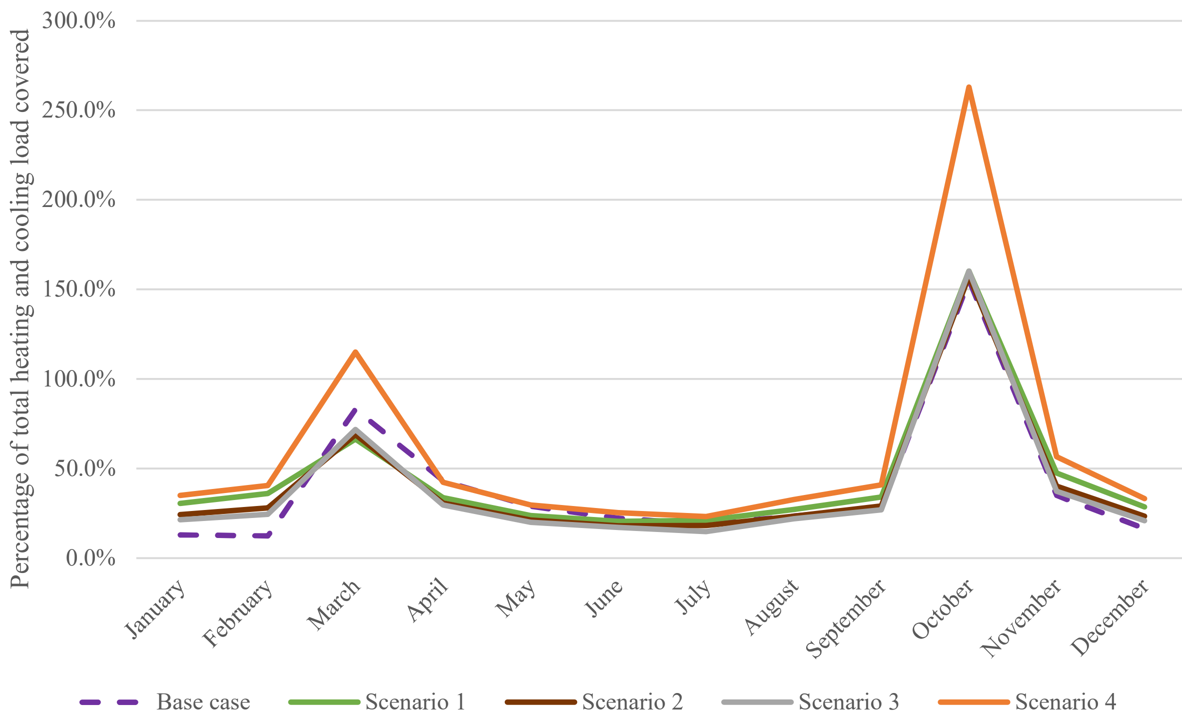

Figure 2.12. Average of monthly total heating and cooling covered by the HGHE coupled with a heat pump system.

The results for every scenario demonstrate that the presence of a greenhouse above the HGHE improves its performance for heating. On the other hand, there is not much difference during cooling periods. The system's ability to meet the heating and cooling demands varies throughout the year, with peak months like December, January, February, June, and July posing a challenge as the system can cover less than 50% of the total energy consumption, regardless of the scenario. In contrast, the system can meet the entire energy consumption during October, since energy demand is less important. It is therefore important to evaluate load coverage during months with extreme temperatures. The following results focus on the months of February for the heating season and July for the cooling season (Table 2.7; Figure 2.13). During the other months, the system covers a higher percentage of the heating and cooling demand; results are given in Appendix I.

Table 2.7. COP values calculated for February and July from LFT.

	Base Case	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
February (1st year)	3.78	3.96	3.88	3.84	3.80
February (5th year)	3.80	3.98	3.90	3.87	3.80
July (1st year)	6.90	6.85	6.79	6.77	6.63
July (5th year)	6.84	6.58	6.74	8.65	6.60

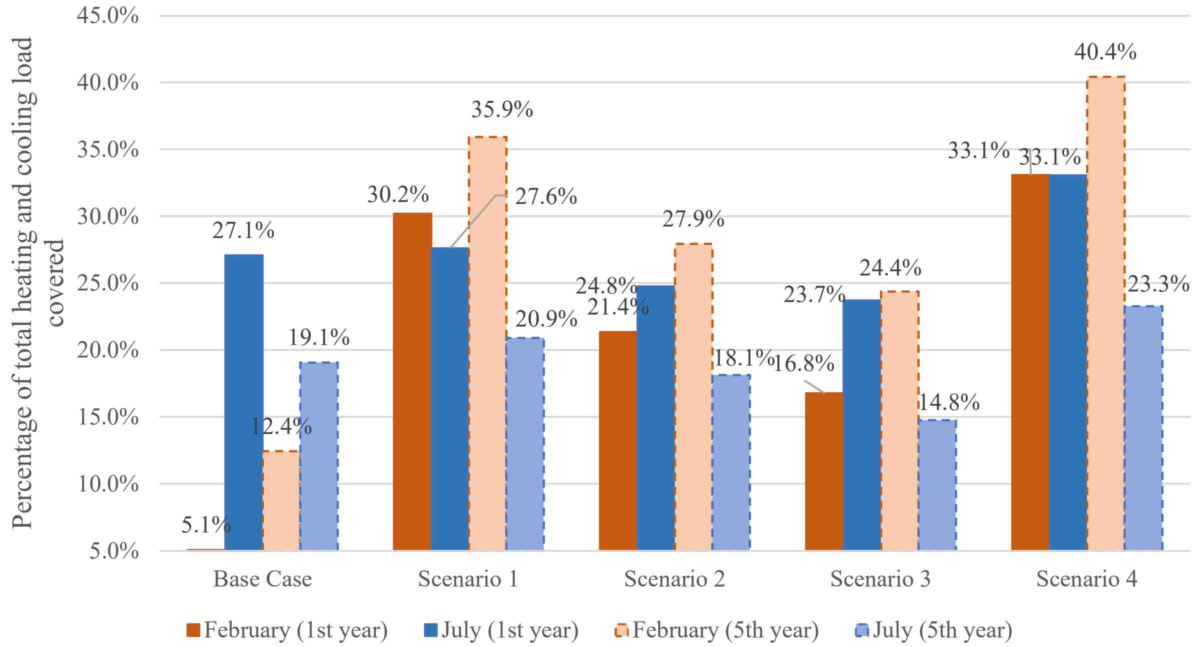

Figure 2.13. Heating and cooling loads covered for February and July.

COP values shown in Table 2.7 are higher than the base case for every scenario in heating mode, while they are lower in cooling mode. There is a 0 – 0.18 increase for the month of February, while the values decrease by between 0.05 – 0.27 for the month of July when comparing every scenario with the base case. In heating mode, Scenario 1 has the best impact on the heat pump COP. The findings indicate that incorporating a greenhouse structure above the HGHE enhances the heating capacity while deteriorating the cooling capacity.

The results for the peak months of February and July suggest that the presence of a greenhouse above the HGHE improves the system performance for heating but slightly lowers the percentage covered during cooling phases. The following comparisons between scenarios and the base case are made for the same year to make comparisons easier. Scenario 1, which implies installing the HGHE at a 1 m depth, increases the load covered in February by 23% to 25%, and increases it by 0.5% in July. Scenario 2 increases the load covered in February by around 15%, while it reduces the load covered in June by around 2%. Scenario 3, which implies installing the HGHE at a depth of 2 m, increases the load covered by around 12% during February, while lowers it by 3% during July. Scenario 4, which combines scenarios 1 and 3, improves both heating and cooling by 28% and 6%, respectively. When looking only at the heating demand, Scenario 4 covers the highest percentage of total heating load, followed by Scenario 1, Scenario 2, Scenario 3 and the base case. When looking only at the cooling demand, Scenario 4 covers the highest percentage of total cooling load, followed by Scenario 1, the base case, Scenario 2 and Scenario 3. Figure 2.13 shows that the system exhibits better performance in terms of heating during the 5th year, whereas it performs better in terms of cooling during the first year. For the heating season, there is a 6% - 8% increase between the first and the fifth year. In contrast, total cooling generally decreases 8% - 10% between the first and fifth year. This can be attributed to a warming ground temperature either caused by the unbalanced HGHE heat injection versus extraction or by the transient propagation of the thermal front from the greenhouse floor into the subsurface. It can be assumed that the constant temperature of the greenhouse increases the subsurface temperature through time.

2.5 Sensitivity Analysis

COP values are shown for the base case and for Scenario 2 (Tables 2.8, 2.9). These tables only display values for the months of February and July, which are representative of the highest and lowest yearly temperatures. It is important to note that the data presented in these tables do not represent the other months. The rest of the results can be found in Appendix I.

Table 2.8. Base case - sensitivity analysis showing COP values for February and July.

	Base case	**Ground surface temperature increased**	**Ground surface temperature reduced**	**Deteriorated ground thermal properties**	**Improved ground thermal properties**
February (1st year)	3.62	3.64	3.63	3.63	3.64
February (5th year)	3.69	3.70	3.68	3.68	3.69
July (1st year)	6.79	6.75	6.84	6.73	6.82
July (5th year)	5.19	5.63	5.20	4.57	5.35

Table 2.9. Scenario 2 - sensitivity analysis showing COP values for February and July.

	Scenario 2	**Ground surface temperature increased**	**Ground surface temperature reduced**	**Deteriorated ground thermal properties**	**Improved ground thermal properties**
February (1st year)	3.78	3.78	3.78	3.73	3.84
February (5th year)	3.85	3.85	3.84	3.80	3.88
July (1st year)	6.75	6.72	6.75	6.69	6.78
July (5th year)	5.46	6.12	5.47	4.60	6.11

When compared with the base case, results (Table 2.8) show that increasing and decreasing ground temperature and changing ground thermal properties does not significantly impact the COP in heating mode. There is also no significant change during the first year in cooling mode. During the fifth year in cooling mode, increasing, and decreasing ground surface temperature results in COP changes of 0.44 and -0.03, respectively, while deteriorating and enhancing ground thermal properties results in changes of -0.62 and 0.16, respectively.

When compared with Scenario 2, results (Table 2.9) show that increasing and decreasing ground temperature and changing ground thermal properties does not significantly impact the COP in heating mode. There is also no significant change during the first year in cooling mode. During the fifth year in cooling mode, increasing, and decreasing ground surface temperature results in COP changes of 0.66 and 0.01, respectively, while deteriorating and enhancing ground thermal properties results in changes of -0.86 and 0.65, respectively.

These results show that, over a prolonged operation period, increasing ground surface temperature as well as reducing and enhancing ground thermal properties have a greater impact on the COP for Scenario 2 compared to the base case. Since the differences are only significant in the long term, it can be assumed that sustained fluctuations in ambient temperature would be required to impact the system's performance. Results can also be seen in the form of percentages of total heating and cooling load covered by the HGHE (Figures 2.14, 2.15).

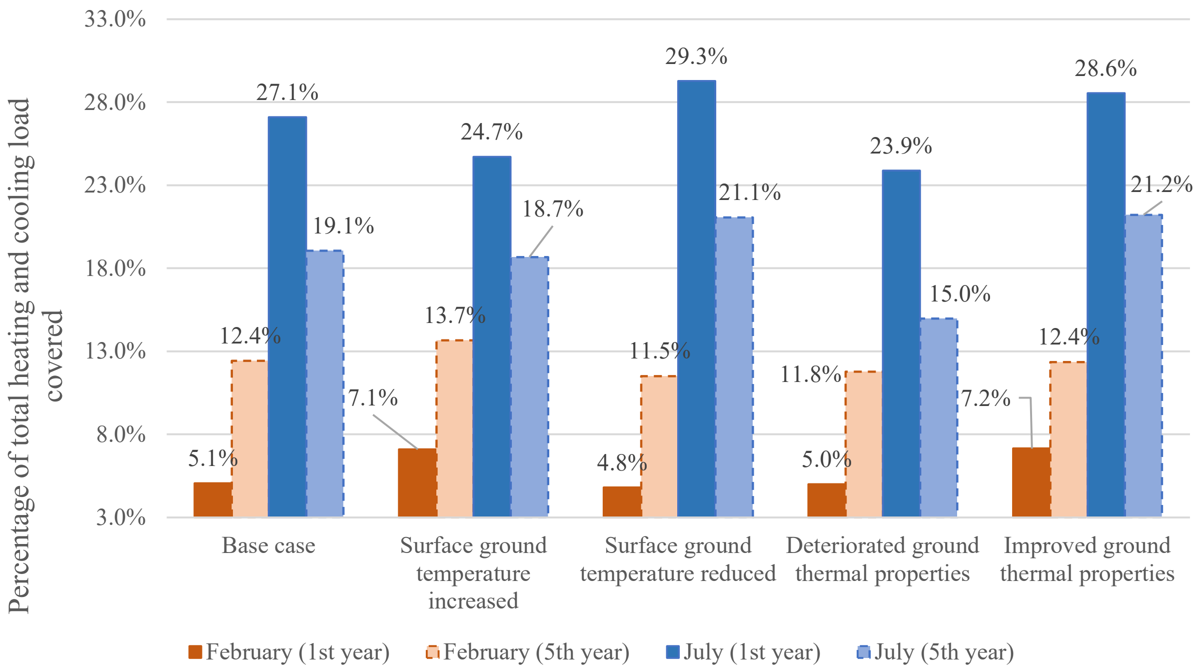

Figure 2.14. Base case - sensitivity analysis results for February and July.

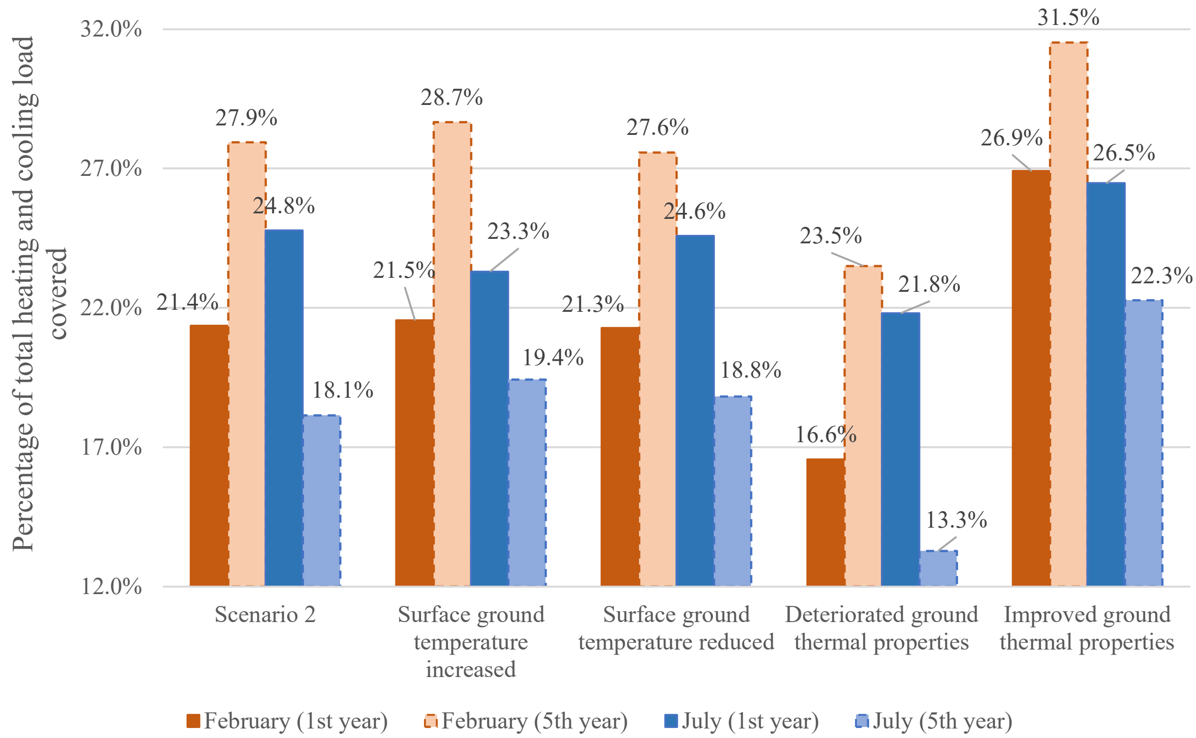

Figure 2.15. Scenario 2 - sensitivity analysis results for February and July.

In the base case (Figure 2.14), variations in ground surface temperature and thermal properties have limited impact on load coverage in heating mode during the first year (-0.3% to 2.1%) and the fifth year (-0.9% to 1.3%). In cooling mode, variations have larger impact than on heating mode during the first (-2.4% to 2.2%) and fifth year (-4% to 2%).

In Scenario 2 (Figure 2.15), variations in ground surface temperature have small effects on load coverage during the first year in heating mode (0.1%), but larger effects during the fifth year (-0.3% to 0.8%). Variations in ground thermal properties have a more important impact on both the first and the fifth year (-4.8% to 5.5%). In cooling mode, variations in ground surface temperature have a smaller effect on both the first and the fifth year (-1.5% to 1.3%), while thermal properties have a larger impact on both the first and the fifth year (-4.8% to 4.2%).

These results indicate that ambient temperature plays a smaller role in the system's performance if a greenhouse with a constant temperature is located above it. In this case, ground thermal properties play an important role in the HGHE's performance, especially during cooling phases. In the base case situation, ambient temperature and ground thermal properties are both equally important.

2.6 Discussion

Numerical model limitations include neglecting surface water infiltration which could be caused by rain and/or greenhouse plant watering, which can impact subsurface heat transport. The applied temperature profile only includes constant temperature for every month, which can vary on an hourly and daily basis. The energy consumption profile considered constant every month can also vary hourly and throughout the day. The LFT was therefore simplified, using a constant temperature of -4 °C during heating periods and 34 °C during cooling periods, while it should be fluctuating during the day. The model therefore has limitations such as simplified assumptions, lack of validation and the homogeneity of those assumptions. To overcome these limitations, attention should be focused on incorporating more realistic scenarios, validating the models against experimental data, considering a higher range of variables, and addressing the heterogeneity and variability of relevant factors.

This study follows Fujii's approach (Fujii et al., 2012) and did not explore alternative arrangements. Covering a higher building load with a similar system could be achieved by using thermally improved pipes or reducing the pitch of the coils, as Chong et al. (Chong et al., 2013) indicated. Using pipes with a larger diameter and increased thermal properties would also be beneficial to the system performance.

Despite these limitations, our results show that an HGHE with a restricted surface area underneath a greenhouse can provide base loads for heating and cooling a greenhouse in a cold continental climate like that of Quebec but is insufficient to cover the full heating and cooling loads. The different scenarios show that there are ways of increasing the quantity of heat produced during winter, but still not enough to only rely on the HGHE and the heat pump system. An auxiliary system should be considered in an urban setting where the area covered by the HGHE is limited. Olabi et al. (Olabi et al., 2020) proposed many hybrid geothermal systems, like solar energy systems and a cooling tower coupled with the geothermal system. The former implies that thermal solar collectors, such as photovoltaic thermal hybrid systems, are used to generate additional heat energy to cover any deficit from the geothermal system, also allowing the GHE to act as a seasonal energy storage option. Such a system is difficult to install on the roof of a greenhouse, as it would prevent the sun from penetrating the building and heating the interior. The latter aims to increase the COP by improving the system cooling capacity with cold-water circulation, which allows the hybrid system to maintain soil thermal balance throughout the year. This kind of system can also be coupled with a borehole GHE, as suggested by Zhou et al. (2022) who designed a system combining a borehole GHE and an HGHE. Their approach reduces the cost of conventional borehole GHE heat pump systems by determining the optimal shape factors, building load distribution scheme and the length of the hybrid GHE.

In addition to performance, costs associated with every scenario will likely vary, with Scenario 4 being more expensive than the others since it has two layers of HGHE. In this case, the amount of pipe used is doubled, there is more fluid, and the heat pump might need to cover a higher power demand, which ends up increasing the installation costs. Scenarios 3 and 4 require deeper excavation, which can be associated with moderate increases in the installation costs.

Installing the system beneath the greenhouse offers several advantages. HGHEs are close to the surface and are impacted by atmospheric temperature changes. Cold temperatures will increase the viscosity of the propylene glycol/water mixture, thereby reducing thermal conductivity and heat transfer potential (Hydrosolar, 2022). In cities like Montréal, Québec and La Pocatière, which experience cold winters, the ground temperature near the surface can fall below 0 °C. The inlet fluid temperature, or heat pump LFT, must be lower than the ground temperature to produce heat, which increases the fluid viscosity. Additionally, the fluid can freeze if it contains too much water, which must be prevented. Also, greenhouses are typically constructed on ground level, so excavating the area and installing the system directly beneath the structure is easier than for conventional residential or commercial buildings and would have potentially lower installation costs.

Fujii's work (2012) was done to simulate a two-week TRT test on a horizontal HGHE, which means that numerical simulations were only carried out for 2 weeks. Comparing these previous two-week simulations and the current five-year simulations based on the same modelling strategy implies distinct variations in ground temperature due to the longer duration of our simulations. Fujii's study demonstrates that the model is well calibrated to reproduce the experimental data. Boundary conditions and input parameters are consistent with those used in the experiment. Predicting the operating temperature of a HGHE for 5 years is more challenging since calibration can be more difficult over such a long period. An HGHE simulation over 5 years can provide more information on the long-term performance of the system under different environmental conditions, but errors or inaccuracies in the model may accumulate over time and result in differences from the real system behavior. Changes in air temperature, humidity, and solar radiation can vary significantly during the five-year period and were assumed constant for our simulations, which is also an important limitation. Thus, our modelling strategy consisted in comparing simulations scenarios in between each other to evaluate the impact of the greenhouse above the HGHE assuming the change in boundary conditions is characteristics of the main effects induced by the greenhouse.

The purpose of the sensitivity analysis was to assess the system's response to changes in key parameters and assess their relative importance. We acknowledge that changing ground thermal properties values may deviate from the conditions under which the model was calibrated. This variation can affect the accuracy of the results and undermine its validity. Therefore, it is essential to interpret the results of the sensitivity analysis with caution. It should be considered as a step towards understanding the behavior of a HGHE system under certain conditions, rather than a validation of the model for a larger range of conditions. Future studies should also focus on model validation under a wider range of conditions, including ground thermal properties and ambient temperature.

The Géotherma Solutions Inc. study (Géotherma Solutions Inc., 2022) showed that an HGHE below the greenhouse would not be enough to produce and inject heat to cover the building's total energy consumption. Using analytical solutions, they showed that the HGHE surface area must be 4 to 9 times bigger than the that of the greenhouse to cover its full heating and cooling loads. It is only possible to cover 25% of the total heating and cooling loads with a reduced HGHE area equal to that of the greenhouse. This method did not take into consideration the effect of the constant greenhouse temperature on the system's performance. Using sizing calculations, Léveillée-Dallaire et al. (2022) showed that 30% to 40% of the heating and cooling peak loads can be covered by a HGHE of the same size as the greenhouse, without considering the effect of the constant greenhouse temperature. With our numerical approach, we calculated that the system could cover 7.1% of the heating and 26.5% of the cooling loads during the coldest and hottest months when there is no greenhouse above the HGHE. Although the percentage of loads covered varies from one study to another, which can be explained by the different methods and model inputs considered, all studies similarly concluded that a HGHE with an area equivalent to that of a greenhouse is insufficient to cover the full heating loads. A hybrid system is required if HGHE space is limited.

Comparison between results for the base case and Scenario 2 during February and July indicate that installing the HGHE under a greenhouse can double the heating loads covered by the system, while slightly lowering the cooling loads covered. This shows that the constant greenhouse temperature has a positive effect on heat extraction. Comparison between Scenario 1, 2 and 3 demonstrates that the closer the system is to the surface (Scenario 1), the better the heat extraction. However, installing a deeper HGHE does not seem to improve either the heating or the cooling performance of the system. Furthermore, Scenario 4 appears to be the best in terms of heating and cooling performance, being able to cover an additional 30%

of heating and 6% of cooling compared to the base case in the short term. Hence, for space optimization, it would be worth choosing this scenario to cover the maximum amount of heating and cooling possible, while further studies need to be done to evaluate if extra costs outweigh the system's benefits.

The sensitivity analysis indicates that a constant greenhouse temperature reduces the system's dependence on ground surface temperature variations for both heating and cooling, even though cooling is less efficient. Hence, there is a notable advantage for heating periods and a small disadvantage for cooling periods. It can therefore be assumed that using such a system has an overall positive effect on the HGHEs performance in cold regions such as Quebec. The analysis results also put emphasis on the importance of measuring ground thermal properties either by performing a TRT or by analyzing ground samples. This shows that system performance can vary according to the type of geological materials affecting the thermal properties. This specific HGHE's percentages of total heating and cooling loads covered are obviously expected to differ for HGHEs located in different environments but results can be used as guidelines for greenhouses in a cold continental climate.

2.7 Conclusions

This work showed that installing a greenhouse over an HGHE can increase the heating capacity of the system, but at the expense of a slightly lower cooling capacity. Heating and cooling performance vary according to the depth of the HGHE installation. Additionally, the simulated system showed improved heating performance while cooling capacity decreased over time. This variation is either caused by the HGHE removing heat more effectively in the cooling phase than it did in the heating phase or by the constant greenhouse temperature spreading heat into the subsurface. Overall, results indicate that incorporating greenhouses over HGHEs can be an effective way to improve heating capacity under certain conditions, but special attention should be paid to their effect on cooling capacity. Considering heating only, between all scenarios, Scenario 4 covers the highest percentage of total heating demand, followed by Scenario 1, Scenario 2, Scenario 3 and the base case.

Sensitivity analysis shows that changes in ground surface temperature affect the system performance with increasing operation time, while ground thermal properties play an important role in the performance of the HGHE, especially during cooling phases. In addition, ground surface temperature variations seem to play a smaller role in the system's performance with a constant temperature greenhouse located above it, when compared to standard HGHEs. Results also indicate the importance of measuring ground thermal properties before installing such a system.

Therefore, the study confirms that a minimum of 7.1% and 26.5% of a small greenhouse's total heating and cooling loads, respectively, can be covered on the first year of operation by an HGHE at a 1.5 m depth with no greenhouse above it (base case). In contrast, installing this same HGHE under a greenhouse with a constant temperature of 21 °C (Scenario 2) increases the heating loads covered to 22.8% but decreases the cooling loads covered to 24.2%.

The significance of this study lies in the exploration of coupling greenhouses with HGHEs for improved heating efficiency in urban agriculture. This knowledge is important for urban greenhouse farmers and policymakers seeking sustainable methods to address heating and cooling demands while minimizing energy consumption and costs. Understanding the trade-off between heating and cooling efficiency is essential for decision-making. The insights gained can inform the design of green-house-HGHE systems in various urban settings for specific geographic location.

Following this study, results could be improved by developing numerical models including the effect of vertical fluid flow to represent precipitation and/or plant watering, which most likely impacts subsurface heat transport. Simulations should also be done with a complete energy consumption profile, which should be determined hourly to represent actual heating and cooling demand. LFT simulations should take into account hourly consumption and select temperatures based on the time of day.

III. Conclusions

1. Synthèse des Résultats

Le premier chapitre de cette étude s'est basé sur une approche analytique, en réalisant le dimensionnement des échangeurs de chaleur horizontaux pour une serre à Montréal considérant un profil de consommation d'énergie horaire et une évaluation de la température du sol à partir de données mesurées (Enerprox, 2022; Government of Canada, 2021). Cependant, l'effet de la température de la serre sur le système n'a pas été pris en compte. De plus, afin d'étudier la possibilité d'installer les ÉCGHs dans un espace limité, un système ayant une superficie similaire à la serre a été simulé pour connaître le pourcentage de charges de chauffage et de refroidissement qu'il peut couvrir.

Le deuxième chapitre a permis d'approfondir les travaux du premier en utilisant des simulations numériques pour étudier les performances des ÉCGHs qui seraient situés sous une serre. Les simulations du deuxième chapitre ont été effectuées à l'aide d'un simulateur à éléments finis, ce qui permet une résolution plus précise des équations de transfert de chaleur et de masse. De plus, contrairement au premier chapitre, le deuxième chapitre a pris en compte l'effet de la température au plancher de la serre sur les performances des échangeurs de chaleur. Dans ce cas d'étude réalisé pour une site de La Pocatière, le profil de consommation d'énergie n'était disponible qu'à une résolution mensuelle, ce qui est un facteur limitant l'interprétation des résultats. De plus, la température non perturbée du sol a été calculée en utilisant des données de température atmosphérique, tandis que la température de la serre a été fixée à 21 °C pour toute l'année afin d'étudier son effet sur les échangeurs de chaleur horizontaux. Les simulations ont été menées sur une période de cinq ans.

En ce qui concerne les limitations de ces deux chapitres, l'effet de la température de la serre sur le système n'a pas été pris en compte dans le premier chapitre, ce qui semble avoir eu un impact significatif sur les performances des échangeurs de chaleur numériquement simulés. Dans le deuxième chapitre, l'utilisation de données mensuelles pour le profil de consommation d'énergie peut également affecter l'interprétation des résultats. De plus, l'hypothèse d'une température constante à 21 °C pour la serre n'est pas nécessairement réaliste, car la température de la serre varie en fonction des conditions météorologiques et des cultures qui y sont réalisées. L'approche du premier chapitre semble surestimer le pourcentage de charges de chauffage et climatisation couvertes, tandis que l'approche du deuxième chapitre est considérée comme plus représentative d'un système réel.

Cette surestimation peut être attribuée à plusieurs facteurs. Tout d'abord, la différence entre la serre de Montréal, qui est une serre ouverte, et celle de La Pocatière, qui est une serre fermée installée dans un climat légèrement plus froid, implique des charges de chauffage et de climatisation différentes. En effet, le profil de consommation d'énergie de la serre fermée à La Pocatière démontre une plus grande demande en chauffage et de climatisation que la serre ouverte, malgré leur superficie similaire. De plus, dans le premier chapitre, les ÉCGHs modélisés étaient optimisés pour minimiser l'espace en utilisant des tuyaux de plus grand diamètre et en éliminant l'espace entre chaque tranchée. En revanche, le système d'ÉCGH modélisé dans le deuxième chapitre était plus conventionnel, utilisant des tuyaux de dimensions standard et une conductivité thermique plus faible. En outre, la différence de température atmosphérique entre Montréal et La Pocatière joue également un rôle important dans les résultats. Étant donné qu'il est plus facile de chauffer un bâtiment pendant la saison hivernale dans une région à climat plus chaud comme Montréal, cela peut avoir un impact significatif sur les charges de chauffage nécessaires. Il est donc essentiel de prendre en considération ces différents facteurs lors de l'analyse des résultats afin d'obtenir une évaluation précise et réaliste des performances des systèmes de chauffage et de climatisation.

Pour continuer à améliorer les résultats de cette étude, des travaux futurs pourraient inclure le développement d'un modèle couplé serre-sol pour mieux prendre en compte l'interaction entre la température de la serre et le système d'échangeur de chaleur. De plus, l'utilisation de données de consommation d'énergie à une résolution plus fine permettrait de mieux représenter les fluctuations horaires de la demande en énergie. Enfin, la prise en compte des pertes de chaleur et d'humidité dans le modèle pourrait également améliorer les résultats.

2. Conclusions

Cette étude faisait partie d'un projet de recherche multidisciplinaire visant à examiner les défis sociaux et techniques et les possibilités d'intégrer des serres dans les quartiers marginalisés de Montréal. Cette étude visait à fournir des outils aux groupes communautaires pour réduire les coûts d'installation des technologies vertes utile au chauffage et à la climatisation des serres urbaines.

Les résultats démontrent que, dans les régions à climat plus froid tels que la province de Québec, les systèmes de pompe à chaleur géothermique avec échangeurs de chaleur horizontaux sont plus efficaces pour la climatisation que pour le chauffage des bâtiments. Même si l'installation d'une pompe à chaleur géothermique sous une serre permet d'augmenter la capacité de chauffage fournie par le système, celui-ci demeure plus performant en mode de climatisation. Étant donné les coûts élevés d'installation, l'utilisation d'un système géothermique dans un espace urbain limité pour une serre est justifiée uniquement si la climatisation est nécessaire et si les opérateurs ont les moyens financiers d'assumer ces coûts d'installation. Les serres fermées sont typiquement climatisées alors que les serres ouvertes ne le sont pas. Un système de pompe à chaleur géothermique serait à envisager pour une serre fermée ou semi-fermée. L'installation du système sous la serre permet de réduire les coûts d'installation, mais ne peut pas répondre à tous les besoins en matière de chauffage et de climatisation. Cette option représente donc un compromis entre les coûts d'installation et les capacités du système. Un système de pompe à chaleur géothermique peut également couvrir des besoins en chauffage et en climatisation plus importants si l'espace n’est pas limité et peut accueillir une surface plus étendue pour les échangeurs de chaleur horizontaux.

Pour un opérateur cherchant à réduire les coûts à long terme liés à la consommation d'électricité, ce système représente donc une option coûteuse mais efficace. Le scénario 4, qui implique deux étages d'échangeurs de chaleur, constitue une option plus coûteuse offrant un rendement supérieur du système de pompe à chaleur dans le cas d'une serre à espace limité. Il est également important de prendre en compte la profondeur d'installation du système géothermique pour améliorer les performances de chauffage et de climatisation. De plus, il convient de souligner que la durée de vie des systèmes de pompe à chaleur est d'environ 25 ans, ce qui permet de récupérer les coûts d'installation grâce aux économies d'électricité réalisées pendant cette période.

Références

Ahamed, M. S., Guo, H., & Tanino, K. (2019). Energy saving techniques for reducing the heating cost of conventional greenhouses. Biosystems Engineering, 178, 9–33. https://doi.org/10.1016/j.biosystemseng.2018.10.017

Bach, C. E., & McClintock, N. (2021). Reclaiming the city one plot at a time? DIY garden projects, radical democracy, and the politics of spatial appropriation. Environment and Planning C: Politics and Space, 39(5), 859–878. https://doi.org/10.1177/2399654420974023

Casasso, A., & Sethi, R. (2014). Efficiency of closed loop geothermal heat pumps: A sensitivity analysis. Renewable Energy, 62, 737–746. https://doi.org/10.1016/j.renene.2013.08.019

Chiasson, A. D. (2016). Geothermal Heat Pump and Heat Engine Systems: Theory and Practice. John Wiley & Sons.

Chiriboga, G., Capelo, S., Bunces, P., Guzmán, C., Cepeda, J., Gordillo, G., Montesdeoca, D. E., & Carvajal C, G. (2021). Harnessing of geothermal energy for a greenhouse in Ecuador employing a heat pump: Design, construction, and feasibility assessment. Heliyon, 7(12), e08608. https://doi.org/10.1016/j.heliyon.2021.e08608

Chong, C. S. A., Gan, G., Verhoef, A., Garcia, R. G., & Vidale, P. L. (2013). Simulation of thermal performance of horizontal slinky-loop heat exchangers for ground source heat pumps. Applied Energy, 104, 603–610. https://doi.org/10.1016/j.apenergy.2012.11.069

COMMUNOSERRE. (2022). Le projet [Site internet]. https://www.communoserre.info/le-projet.html

De Rosa, M., Gainsford, K., Pallonetto, F., & Finn, D. P. (2022). Diversification, concentration and renewability of the energy supply in the European Union. Energy, 253, 124097. https://doi.org/10.1016/j.energy.2022.124097

Decagon Devices, Inc. (2016). KD2 Pro Thermal Properties Analyzer [Manuel de l'opérateur]. http://manuals.decagon.com/Manuals/13351_KD2%20Pro_Web.pdf

Diersch, H.-J. G. (2013). FEFLOW: Finite Element Modelling of Flow, Mass and Heat Transport in Porous and Fractured Media. Springer Science & Business Media.

Enerprox. (2022). Sommaire étude Biopterre [Rapport interne]. Enerprox. Canada.

Farabi-Asl, H., Fujii, H., & Kosukegawa, H. (2018). Cooling tests, numerical modelling and economic analysis of semi-open loop ground source heat pump system. Geothermics, 71, 34–45. https://doi.org/10.1016/j.geothermics.2017.08.005

Fujii, H., Nishi, K., Komaniwa, Y., & Chou, N. (2012). Numerical modelling of slinky-coil horizontal ground heat exchangers. Geothermics, 41, 55–62. https://doi.org/10.1016/j.geothermics.2011.09.002

Fujii, H., Yamasaki, S., Maehara, T., Ishikami, T., & Chou, N. (2013). Numerical simulation and sensitivity study of double-layer Slinky-coil horizontal ground heat exchangers. Geothermics, 47, 61–68. https://doi.org/10.1016/j.geothermics.2013.02.006

Giordano, N., Langevin, H., & Molson, J. (2022). Étude de préfaisabilité d'un système géothermique à air pulsé pour chauffer et climatiser un bâtiment de recherche qui sera construit à Sainte-Anne-de-la-Pocatière, Québec [Rapport préliminaire confidentiel]. Geotherma solutions inc. Canada.

Government of Canada. (n.d.). Canadian climate normals 1981-2010 station data for Montréal/Pierre Elliott Trudeau International Airport [Site internet]. Gouvernement du Canada. Canada. https://climat.meteo.gc.ca/climate_normals/results_f.html?searchType=stnName&txtStationName=la+poca&searchMethod=contains&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=5806&dispBack=1

Government of Canada. (2021). Données des stations pour le calcul des normales climatiques au Canada de 1971 à 2000, MONTREAL/MIRABEL INT'L A, Température du sol [Site internet]. Gouvernement du Canada. Canada. https://climat.meteo.gc.ca/climate_normals/results_f.html?stnID=5616&dispBack=1&month1=9&month2=12

Gundersen, C., Hake, M., Dewey, A., & Engelhard, E. (2021). Food Insecurity during COVID-19. Applied Economic Perspectives and Policy, 43(1), 153–161. https://doi.org/10.1002/aepp.13100

Hein, P., Kolditz, O., Görke, U.-J., Bucher, A., & Shao, H. (2016). A numerical study on the sustainability and efficiency of borehole heat exchanger coupled ground source heat pump systems. Applied Thermal Engineering, 100, 421–433. https://doi.org/10.1016/j.applthermaleng.2016.02.039

Hou, G., Taherian, H., Song, Y., Jiang, W., & Chen, D. (2022). A systematic review on optimal analysis of horizontal heat exchangers in ground source heat pump systems. Renewable and Sustainable Energy Reviews, 154, 111830. https://doi.org/10.1016/j.rser.2021.111830

Hydrosolar. (2022). Why and When Horizontal Geothermal Fail to Deliver Energy Savings. Advanced Technical Zone [Site internet]. https://hydrosolar.ca/blogs/advanced-technical-zone/why-and-when-horizontal-geothermal-fail-to-deliver-energy-savings

IPCC. (2014). Summary for Policy Makers: Working group 11 contribution to the fifth assessment report of the Intergovernmental panel on Climate Change [Rapport publique]. Cambridge University Press. USA. https://www.ipcc.ch/report/ar5/syr/

Lalonde, T., Monfet, D., & Haillot, D. (2021). Proposition of a humidity control strategy for a calibrated greenhouse model with realistic controls in TRNSYS [Article de conférence]. École des technologies supérieures. Canada. https://www.conftool.com/esim2020/index.php?page=browseSessions&form_session=38#paperID1244

Langevin, H. (2022). Étude des systèmes de pompe à chaleur géothermique et de stockage thermique souterrain en région nordique: Aspects souterrains [Mémoire de maîtrise]. INRS, Centre Eau, Terre et Environnement. Canada. https://espace.inrs.ca/id/eprint/13192/

Langevin, H., Giordano, N., Raymond, J., & Gosselin, L. (2023). Oscillatory thermal response test using heating cables: A novel method for in situ thermal property analysis. International Journal of Heat and Mass Transfer, 202, 123646. https://doi.org/10.1016/j.ijheatmasstransfer.2022.123646

Lazzarin, R. (2020). Heat pumps and solar energy: A review with some insights in the future. International Journal of Refrigeration, 116, 146–160. https://doi.org/10.1016/j.ijrefrig.2020.03.031

Lepage, N. (1996). Modélisation tridimensionnelle régionale et locale de l'écoulement de l'eau souterraine sur l'île de Montréal et au Centre de Tri et d'Élimination des déchets de la ville de Montréal. [Mémoire de maîtrise]. INRS, Centre Eau, Terre et Environnement. Canada.

Léveillée-Dallaire, X., Comeau, F.-A., & Raymond, J. (2020). Évaluation du potentiel géothermique des échangeurs de chaleur hybrides : Boucle verticale semi-ouverte avec convection de l'eau souterraine du puits [Rapport technique]. INRS, Centre Eau, Terre et Environnement. Canada. https://espace.inrs.ca/id/eprint/11752/

Léveillée-Dallaire, X., & Raymond, J. (2022). Sizing Horizontal Geothermal Heat Exchangers for Community Greenhouses in Montreal [Article de conférence]. 2022 Geothermal Rising Chapter, 46, 793–803. INRS, Centre Eau, Terre et Environnement. Canada.

Léveillé-Guillemette, F., & Monfet, D. (2018). Calibration d'un modèle énergétique et analyse économique de mesures de conservation d'énergie d'une serre communautaire à Montréal [Article de conférence]. eSim 2018 « Building Simulation to support Building Sustainability ». École de technologie supérieure, Canada. http://cretau.ca/wp-content/uploads/2019/04/2-3-B-2-Calibrationdunmodlenergtiqueetanalyseconomiquedemesuresdeconservation.pdf

Lund, E. M., Forber-Pratt, A. J., Wilson, C., & Mona, L. R. (2020). The COVID-19 pandemic, stress, and trauma in the disability community: A call to action. Rehabilitation Psychology, 65, 313–322. https://doi.org/10.1037/rep0000368

Marcotte, D., & Pasquier, P. (2009). The effect of borehole inclination on fluid and ground temperature for GLHE systems. Geothermics, 38(4), 392–398. https://doi.org/10.1016/j.geothermics.2009.06.001

McClintock, N. (2010). Why farm the city? Theorizing urban agriculture through a lens of metabolic rift. Cambridge Journal of Regions, Economy and Society, 3(2), 191–207. https://doi.org/10.1093/cjres/rsq005

Mohamed, M. B. (2003). Geothermal resource development in agriculture in Kebili region, Southern Tunisia. Geothermics, 38(4), 392–398. https://doi.org/10.1016/j.geothermics.2003.07.008

Mok, H.-F., Williamson, V. G., Grove, J. R., Burry, K., Barker, S. F., & Hamilton, A. J. (2014). Strawberry fields forever? Urban agriculture in developed countries: a review. Agronomy for Sustainable Development, 34(1), 21–43. https://doi.org/10.1007/s13593-013-0156-7

Morshed, W., Abbas, L., & Nazha, H. (2022). Heating performance of the PVC earth-air tubular heat exchanger applied to a greenhouse in the coastal area of west Syria: An experimental study. Thermal Science and Engineering Progress, 27, 101000. https://doi.org/10.1016/j.tsep.2021.101000

Nadeau, S. (2019). Stratigraphie et processus sédimentaires dans le chenal de navigation du Port de Montréal [Mémoire de maîtrise]. Université du Québec à Rimouski. Canada. https://semaphore.uqar.ca/id/eprint/1657/

Olabi, A. G., Mahmoud, M., Soudan, B., Wilberforce, T., & Ramadan, M. (2020). Geothermal based hybrid energy systems, toward eco-friendly energy approaches. Renewable Energy, 147, 2003–2012. https://doi.org/10.1016/j.renene.2019.09.140

Ouzzane, M., Eslami-Nejad, P., Badache, M., & Aidoun, Z. (2015). New correlations for the prediction of the undisturbed ground temperature. Geothermics, 53, 379–384. https://doi.org/10.1016/j.geothermics.2014.08.001

Prest, V. K., & Keyser, J. H. (1982). Caractéristiques géologiques et géotechniques des dépôts meubles de l'Ile de Montréal et des environs, Québec [Carte]. Commission géologique du Canada. Canada. https://donnees.montreal.ca/ville-de-montreal/geologie-des-depots-meubles

Sangi, R., & Müller, D. (2018). Dynamic modelling and simulation of a slinky-coil horizontal ground heat exchanger using Modelica. Journal of Building Engineering, 16, 159–168. https://doi.org/10.1016/j.jobe.2018.01.005

Savard, M. M. (2013). Canadian Inventory of Groundwater Resources: Integrated regional hydrogeological characterization of the fractured aquifer system of southwestern Quebec [Rapport publique]. Geological Survey of Canada. Canada. https://publications.gc.ca/site/eng/443463/publication.html

Schupp, J. L. (2017). Cultivating Better Food Access? The Role of Farmers' Markets in the U.S. Local Food Movement. Rural Sociology, 82(2), 318–348. https://doi.org/10.1111/ruso.12124

Spacey, J. (2017). 11 Types of Urban Agriculture. Simplicable [Site internet]. https://simplicable.com/new/urban-agriculture

Tang, F., & Nowamooz, H. (2020). Outlet temperatures of a slinky-type Horizontal Ground Heat Exchanger with the atmosphere-soil interaction. Renewable Energy, 146, 705–718. https://doi.org/10.1016/j.renene.2019.07.029

Williams, G. P., & Gold, L. W. (1977). Les températures du sol. Conseil national de recherches du Canada. Division des recherches en construction, 7 p. https://doi.org/10.4224/40000922

Xiong, Z., Fisher, D. E., & Spitler, J. D. (2015). Development and validation of a SlinkyTM ground heat exchanger model. Applied Energy, 141, 57–69. https://doi.org/10.1016/j.apenergy.2014.11.058

Zhang, S., Guo, Y., Zhao, H., Wang, Y., Chow, D., & Fang, Y. (2020). Methodologies of control strategies for improving energy efficiency in agricultural greenhouses. Journal of Cleaner Production, 274, 122695. https://doi.org/10.1016/j.jclepro.2020.122695

Zhou, K., Mao, J., Zhang, H., Li, Y., Yu, X., Chen, F., & Li, M. (2022). Design strategy and techno-economic optimization for hybrid ground heat exchangers of ground source heat pump system. Sustainable Energy Technologies and Assessments, 52, 102140. https://doi.org/10.1016/j.seta.2022.102140

IV. Annexes

Annexe I

Les différents modèles FEFLOW créés et simulés ainsi que les tableaux regroupant tous les résultats des simulations sont disponibles en ligne et peuvent être consultés sur le site web de Boréalis (https://borealisdata.ca/). Pour accéder aux fichiers, il suffit de rechercher le DOI https://doi.org/10.5683/SP3/IJFGG9.