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Optimizing economic performances of foundation earth-to-air heat exchangers for low-technology residential air-conditioning

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ABSTRACT

Despite its classification as a low-technology and nearly passive sustainable system, the use of earth-to-air heat exchangers in residential settings remains relatively uncommon, primarily due to the expenses associated with excavation. Nevertheless, positioning the heat exchanger around the building's foundations during construction offers a potential solution to mitigate these costs. This study conducts an economic viability analysis for such a configuration, focusing on a typical single-family dwelling in Montréal, Canada. A sizing investigation revealed that ducts with relatively small diameters (approximately 20 cm), constructed from cost-effective materials, are optimal. These ducts should be placed as deep and as distant from the foundation as feasible. The optimal heat exchanger configuration reduces the building's heating/cooling load by 701 kWh per year (4.3 %). However, despite minimal excavation expenses, the economic analysis suggests an unviable Levelized cost of Energy for the province of Quebec (0.182 US$.kWh^{-1}) compared to the low electricity rates in the area (a domestic fare of 0.059 US$.kWh^{-1}). The findings underscore notable losses attributable to thermal short-circuiting influenced by the basement walls and coupling affected by the mandatory Heat Recovery Ventilation system. Overall, it was determined that only 60 % of the sensible heat exchanged with the soil effectively contributes to load reduction.

1. Introduction

CONTEXT AND BRIEF LITERATURE REVIEW: As stakeholders exert pressure, climate considerations assume heightened significance in prospective policy frameworks. Internationally, buildings emerge as a primary source of energy consumption, requiring a reduction in emissions from this sector to effectively address climate change challenges. The building sector accounted for 36 % of global final energy consumption and 37 % of CO_2 emissions in 2020 when the construction industry is considered [1]. In particular, the residential sector currently accounts for 22 % of global final energy consumption and 6 % of direct CO_2 emissions [1]. Energy efficiency measures can therefore have a major impact on energy consumption and power demand in this sector. In Quebec, buildings account for 33 % of final energy consumption, and 19 % in the residential sector alone, with about 61 % for space heating [2]. Among these buildings, the housing stock is roughly half single-family homes (44.1 %) and half apartments (46.2 %).

Leveraging ground geothermal potential to improve building temperature regulation is an age-old practice that nowadays presents novel avenues for nearly passive, low-technology environmental systems. An Earth-to-Air Heat Exchanger (EAHE) comprises an underground network of pipes through which air circulates. Capitalizing on the temperature differential between the soil and the air, the system facilitates air cooling in summer and heating in winter. By preconditioning incoming air before it enters a building, the EAHE system effectively reduces the building's heating and cooling load [3]. While the comprehensive scope of geothermal air exchanger applications is detailed in previous literature [3], this study focuses specifically on residential implementations of such systems.

The operational principle of the EAHE system is straightforward: outdoor air, at ambient temperature, is introduced into underground tubes. This fresh air undergoes gradual heating or cooling through heat exchange with the ground, contingent upon seasonal variations. Subsequently, the conditioned air is discharged into the building directly or via auxiliary equipment such as a Heat Recovery Ventilator (HRV), solar chimney, heat pump, or other passive or active mechanisms [3]. In addition to underground pipes, a bypass mechanism is essential to disengage the system when the effects of the ground are undesirable. For example, Flaga-Maryanczyk et al. have documented instances where an air exchanger contributes to cooling ambient air on specific winter days [4]. This bypass system not only facilitates ground recovery from the

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Nomenclature

Symbols

Q_{tot}	Ventilation volumetric flow rate ($L.s^{-1}$)
A_{tot}	House surface area (m^2)
N_{br}	Bedroom number
C_{tot}	Total annualized cost ($US)
E_{prov}	Energy provided (kWh)
C_{inv}	Investment cost ($US)
C_{maint}	Maintenance cost ($US)
C_{carb}	Economic gain link to emission reduction cost ($US)
r_{dis}	Real discount rate
life	System lifetime (year)
r_{inf}	Inflation rate
r_{int}	Interest rate
$Grid_{CO2}$	Carbon content of the electricity grid ($gCO_2eq.kWh^{-1}$)
C_{CO2}	Price of carbon emissions ($US\$.tCO_2eq^{-1}$)
P_{ducts}	Pressure inside the ducts (Pa)
f	Darcy friction factor
L	Length (m)
D	Diameter (m)
v	velocity ($m.s^{-1}$)
ρ_{air}	Air density ($kg.m^{-3}$)
ε	Roughness coefficient (m)
Re	Reynolds number
$P_{junctions}$	Pressure inside the junctions (Pa)
K_f	Losses coefficient
K_m	Constant coefficient for equation (10)
K_i	Constant coefficient for equation (10)
K_d	Constant coefficient for equation (10)

Abbreviations

EAHE	Earth-to-air heat exchanger
HRV	Heat recovery ventilator
EER	Energy Efficiency Ratio
LCOE	Levelized Cost of Energy
CRF	Capital Recovery Factor

exchanger's influence, but also allows the floor to return towards its original temperature during periods of inactivity. Continuous use of the exchanger without intermittent recovery may compromise performance [5,6].

Cekinir and Ozgener compare the application of EAHE and ground Ground-source heat pumps for both heating and cooling purposes, with a particular focus on evaluating the effectiveness of each system [7]. One of the advantages of the EAHE is the absence of refrigerant fluid used in horizontal or vertical Ground-source heat pumps systems. They also mention that in large buildings such as greenhouses, the uniformity of the conditions ensured by the EAHE is also an asset.

Hollmuller and Lachal measured the performance of an EAHE system installed in Switzerland coupled with a solar collector [8]. The savings generated were calculated relative to the equivalent cost of diesel used for heating and ventilation for cooling. The estimated payback period for this investment amounted to 15.7 years.

Xiao and al. proposed experimental and numerical results for EAHE integrated within a greenhouse located in a temperate environment [9]. The authors reported that the night-time temperature of the greenhouse increased by 1.43 °C during winter, while the temperature during summer daytime was reduced by 2.10 °C. In conclusion, the authors state that the system is a viable auxiliary device for greenhouse heating and cooling in cold winter and hot summer regions and to reduce greenhouse gas emissions but do not mention any financial parameters.

Puppala et al. analyzed data for different regions in India to derive necessary geological and climatic parameters to assess EAHE [10]. The study indicates 25 % of excellent sites, while 47 % and 32 % of the areas are classified as moderate or good, respectively. Carbon footprint analysis for India reveals that EAHE adoption can reduce CO2 by 66.2 % compared to conventional air conditioning units.

Ascione et al. demonstrated a strong correlation between the profitability of an EAHE system and the characteristics of the soil into which it is installed [11]. The estimated payback periods (PBPs) for the system across three Italian climates (Milan, Rome, and Naples) ranged from 4.5 to 5.5 years for loose soil (easy excavation), 7.4 to 9.1 years for mildly rocky soil (standard excavation), and 22.8 to 28.1 years for highly rocky soil (difficult excavation). The electricity cost for this analysis has been set at $0.20 per kWh.

Cirillo et al. evaluated the energy performances and economic assessment of the coupling of an earth-to-air heat exchanger to an already existing HVAC system for the Italian territory [12]. In the study, the EAHE was used as a pretreatment for the HVAC of office buildings located in different Italian climatic zones. The study concluded that in the area of Pomezia, characterized by high energy costs, the investment related to precooling with an EAHE permitted a maximum of 78 % of power savings in summer and a corresponding average energy consumption reduction of 23 % to 43 %.

Bansal et al. conducted a detailed study on the influence of the quality of components used in an EAHE system installed in India [13]. They reported a payback period of 3.3 years for a system equipped with an efficient fan and 14.1 years for a standard fan, with an electricity cost of $0.16 per kWh. The impact of the conditioning system replaced by the exchanger was also examined. Payback periods ranged from 5.8 to 51 years depending on its energy efficiency. Consequently, they concluded that if the existing system was sufficiently efficient, therefore the installation of an EAHE would not be economically justified.

Anshu et al. studied the coupling of an EAHE with a photovoltaics system to answer the electric and thermal load of an Indian house [14]. The pipe diameter is identified as having the most impact on performance. An optimum of 70 m of ducts with a diameter of 0.2 m is found. This configuration brings annual gains of 3958.7 kWh for heating and 4158 kWh for cooling, which translate into a payback period between 5 and 10 years.

Xiao and Li discuss the influence of different types of pipes on the heat exchange performance of an earth-air heat exchanger [15]. They reinforce the previous study stating that thin wall pipes "had a negligible effect on EAHE performance" and hence that the cheapest should be chosen with durability in mind. They even suggested corrugated pipes when space is a concern. The authors did not present a financial analysis.

All these studies demonstrate a strong sensitivity of EAHE system performance to climate, soil type, and components used for design, as well as the systems employed for air conditioning. As a result, the economic viability of a system can rapidly become unattainable based on specific parameter variations. Moreover, geothermal exchangers face competition from HRVs, which also contributes to reducing conditioning loads. Given that HRVs involve high efficiencies, are easier to install, and less expensive, EAHE struggle to gain traction in the building sector [16].

One significant challenge of this technology is the high cost associated with tube installation. Excavation expenses vary depending on soil type, with soil that is difficult to excavate potentially rendering the system economically unfeasible.

Yang et al. proposed the use of an air inlet plenum at the beginning of an EAHE, reducing excavation costs through a reduction of the system's size between 50 % and 60 % [17]. Molina-Rodea et al. tested the performances of a vertical EAHE, which requires low excavation depth and low excavated surfaces and still brings a temperature decrease of almost 10 °C [18]. Benhammou et al. proposed an innovative EAHE utilizing a convection zone composed to improve thermal transfers [19]. The proposed EAHE provided the same cooling power as a 31 % longer classical EAHE, bringing interesting economic gains through excavation reduction.

Another strategy to mitigate this issue is to install the EAHE during the construction of the building foundations. Since the soil is already disturbed during foundation construction, excavation costs are minimized. However, with this approach, the space and configurations available for EAHE locations is very restricted.

Kayaci et al. studied the potential of two water-based ground-source heat pumps, one placed in the soil under the foundations, and another placed in the concrete layer of the latter [20,21]. The investigated 2400 m^2 building is located in Istanbul and was monitored from February 8th to March 13th, 2019. Over this period, measurements showed a gain of 5.51 kWh per day for the loop in the soil and 4.63 kWh per day for that located in the concrete slab. The experimental data were used to validate a MATLAB-based finite difference-based thermal model.

Several studies have investigated EAHE installations near foundations. Pfafferott evaluated the performance of three EAHEs installed in different buildings in Germany: one placed beneath the foundation slab and the other two positioned around it [22]. These systems yielded annual gains of 28, 75 and 30 kWh per m^2 of duct surface, with total duct surface areas of 198, 520, and 1650 m^2.

Taurines et al. examined an EAHE incorporated within the foundation footing of a health center, utilizing a French technology called Fondatherm® [23]. In this technology, the air circulates directly inside the foundation footing and thus follows the building foundation outline. A building in France equipped with this type of foundation was studied. With a total tube surface area of 80 m^2, the authors obtained gains of 8.9 kWh per day in heating and 3 kWh per day in cooling over the studied year.

Hsu et al. investigated an EAHE installed within the foundation of a three-story building, with the unique feature being the immersion of ducts in water instead of burial [24]. The systems provided significant cooling performances, similar to a system buried 0.7 m deeper in the soil. On the economic side, the system provides a gain of 703 US$.year^{-1} compared to traditional cooling systems during the cooling period of 7 months. The system costs are estimated at 2280 US$ for the air ducts, 100 US$ for the drainage system, 150 US$ for fans and 0.2 US$.kWh^{-1} for electricity costs. With this parameter the authors calculate a return-on-investment period of four years.

Yang et al. proposed a novel foundation based EAHE configuration using flowing water around the ducts to improve performance. The systems generate a cooling power of 4.84 kW and a heating power of 0.8 kW for a total capital investment of 2060 US$. Whereas for similar performances, a traditional system would require a total capital investment of 4060 US$.

Zhang et al. studied a four ducts EAHE next to the foundation wall of a 2270 m^2 office building [25]. The exchanger is supposed not to have any thermal interaction through the soil with the building. A finite volume method model is compared with the measures in situ and a relative error of 14.8 % is found. This model is then used to optimize the system, and an optimal configuration with a total ducts length of 100 m and a diameter of 100 mm is obtained. The system can fulfill the entire building's cooling demand, as well as reducing heating consumption by 23.3 %.

These four studies underscore the potential for foundation-based Earth-to-Air Heat Exchangers (EAHEs) to yield significant energy gains. However, they primarily pertain to relatively large-scale facilities and do not directly correspond to the present scenario, where the building footprint is considerably smaller. Spitler et al. investigated a heat exchanger surrounding the foundation of a single-family house, but designed for use with a ground-source heat pump and not an EAHE. In that study, the authors employed smaller diameter ducts filled with water instead of air [26].

OBJECTIVES: In this global context, the primary objective of this study is to approximate the economic viability of a foundation EAHE configuration for a single-family residential building located in southern Quebec (Montréal, Canada). The study estimates the heating/cooling load of the residence and subsequently quantifies the savings enabled by the EAHE. These savings are then compared against the material and installation costs to roughly estimate the economic feasibility of the system.

NOVELTY AND HIGHLIGHTS: The novelty of this paper lies firstly in its economic assessment of a small-scale foundation-based EAHE for a typical single-family house in Quebec, offering a low-tech and cost-effective solution for passive reduction of domestic heating and cooling energy consumption. This study explores the energy exchange dynamics between such systems and the building, as well as delineating the specific technological constraints and implementation challenges pertinent to the Quebecois context. This is achieved through a parametric study of the variation of several factors influencing performance, namely the exchanger's tube length, depth, diameter, and distance from foundation walls. These original analyses are completed by the more common investigations of the effects of the variation of the relevant thermophysical properties, such as ground conductivity, location in North America, basement temperature setpoint, basement thermal resistance, HRV efficiency, and ventilation volumetric flow rates.

The main findings based on the research are as follows:

- The EAHE should be located as deep and as far away from the basement as possible, without requiring additional excavation.
- Smaller tube diameters show better economic potential, but attention should be paid to the pressure losses induced by the EAHE. The smallest diameter should be selected without necessitating an additional ventilator due to increasing pressure drops.
- Short-circuiting losses occur when the EAHE is close to the basement walls, while coupling losses occur when the EAHE is coupled with an HRV. Both types of losses are non-negligible, and their behaviors need to be considered in sizing.
- Short-circuiting losses are deeply linked to basement usage and its thermal isolation.
- Coupling losses are deeply linked to the HRV efficiency and the building ventilation rate.
- The material of the ducts has a minimal impact on performance.
- This configuration of EAHE performs similarly across different soil types.
- Given the calculated 40-year payback period, the study indicates limited potential for the system in regions with low electricity rates and mandatory HRV on new constructions, such as Southern Quebec (Canada).

CONTENT: The next section presents the characteristics of the typical reference building along with the model used for load calculation. It also discusses the high-efficiency HRV, required by the Canadian building code, which is used. Section 3 proposes a description of the details of the calculations implemented to determine the impact of the EAHE and the global TRNSYS representation. It also embeds the typical economic parameters used in the study. Then, section 4 involves the results, their description, analysis, and discussion, while the last section involves concluding remarks.

2. Reference building load simulation

One of the specific aspects of this type of study is that it involves installing the heat exchanger in a configuration where it interacts closely with the building, including its foundations and HRV system. A detailed simulation of their behaviors and interactions is essential to comprehensively understand the relationships among these various components. These complexities necessitate the use of a simulation tool such as the TRNSYS simulation environment for conducting the simulations [27].

2.1. House characteristics

Simulations were conducted to determine the annual heating and cooling loads of the house both with and without the EAHE to evaluate the economic benefits of the system. A comparative analysis of these loads was then performed to assess the energy savings facilitated by the EAHE.

The investigated building is a typical average single-family house with the EAHE installed during the building's construction (Fig. 1). The simulations were executed using TRNSYS Type 56. Parameters used were retrieved from the Canadian National Building Code [28] and the National Energy Code of Canada for buildings [29].

In terms of dimensions, the house features a footprint of 67 m^2 and a total heated area of 201 m^2. Thermal resistances for the building envelope, as listed in Table 1, were applied. The house simulation comprises four zones representing the ground floor, first floor, attic, and basement, respectively. The structure stands 8 m tall above ground level and extends 2.5 m underground.

Air exchanges between the house and the exterior are due to infiltration and are regulated by ventilation. For ventilation, equation (1), derived from [30], is employed to determine the total required airflow (Q_{tot}). Given a floor area (A_{tot}) of 200 m^2 and 4 bedrooms (N_{br})., Equation (1) yields a ventilation flow rate of 47.65 $L.s^{-1}$ or 171 $m^3.h^{-1}$. The incoming air temperature and humidity are modulated by both the EAHE and the Heat Recovery Ventilator (HRV).

$$Q_{tot} = 0.15A_{tot} + 3.5(N_{br} + 1) \quad (1)$$

Electrical heaters were selected for temperature control inside the house, as they are the most prevalent type of heater in Canada [31]. For cooling, a system with an Energy Efficiency Ratio (EER) (or cooling coefficient of performance) of 3.5 was chosen based on data compiled by [31]. The basement temperature is maintained above 15 °C year-round, based on the minimal temperature allowed for space not suitable for living [32]. The rest of the house is kept between 20 °C and 25 °C from September to March and between 15 °C and 22 °C from April to August, based on Canadian air conditioning habits [33].

Table 1
Building's thermal resistances (adapted from [28])

Component	Thermal resistance ($m^2K.W^{-1}$)	U value ($W.m^{-2}K^{-1}$)	Corresponding surface (m^2)
Roof	7.22	0.137	77.36
Exterior walls	4.31	0.230	170
Basement walls	2.99	0.334	83.5
Floor	1.12	0.896	201
Slab	0.88	1.121	67
Windows	0.94	1.06	44

The TRNSYS data catalog is used for heat gains due to activity [27]. For the inhabitants, four low-activity people will be considered (120 W each), two computers with monitors (140 W each) and ten 13 W light bulbs. All these gains will be present only when the home is in use: mornings and evenings on weekdays, and all day at weekends. As for the lights, their use will also depend on solar radiation.

2.2. Heat recovery ventilator

The Canadian building code imposes the installation of an HRV in new houses [28]. In this project, the HRV is interconnected in series with the EAHE: air passes through the EAHE, then through the HRV, before being introduced into the house. For this simulation, TRNSYS Type 760 is utilized.

Parameters are derived from the specification sheet of the 65H model by VänEE® [34]. The sensible efficiency of the unit is stated at 0.82 for an air temperature of 0 °C and 0.63 for −25 °C. Within this temperature range, efficiency is assumed to vary linearly, while outside this range, it remains constant, to match the efficiency curves described in [35].

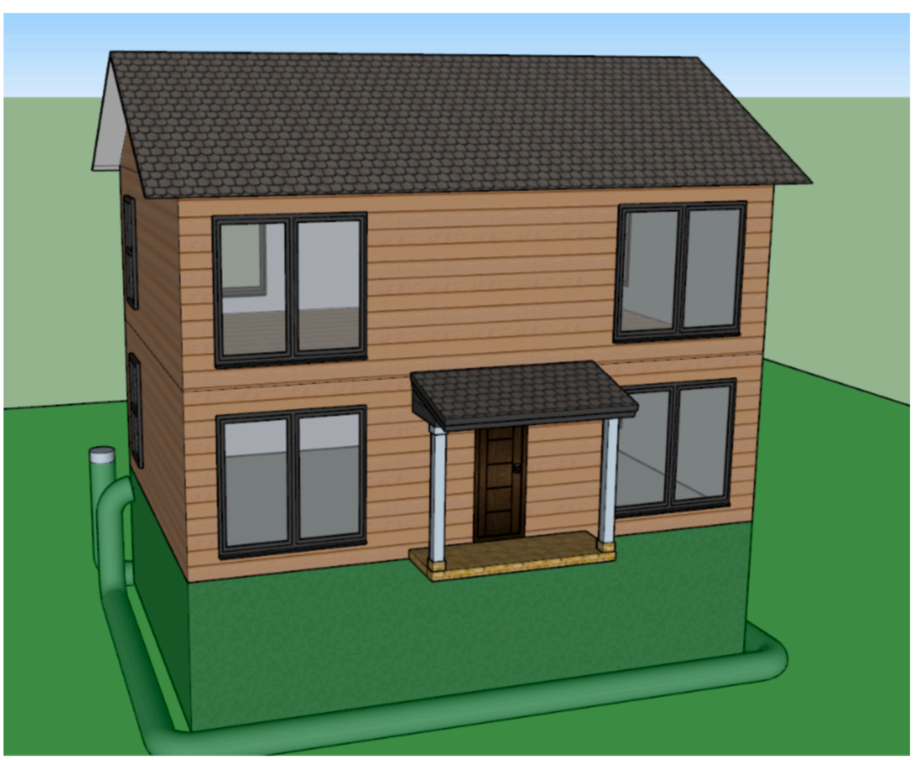

Fig. 1. Schematic representation of the simulated habitation involving the EAHE.

During summer and when outdoor temperatures exceed 20 °C, the HRV is deactivated. Additionally, HRV operation is adjusted when the incoming air temperature is too low, necessitating a defrost cycle. During defrost cycles, the supply fan is deactivated while the exhaust fan continues to operate. The 65H model employs three distinct defrost cycles for temperatures below −5°C, −15 °C, and −27 °C, with corresponding fan shutdown times of 10, 14, and 20 min, respectively. Following the defrost cycle, the HRV operates at higher flow rates to compensate for the shutdown.

The heating and cooling load of the house is simulated using these parameters in conjunction with a Canadian Weather Energy Calculator file from a weather station located in Montreal, Canada. Annual heating and cooling loads of 16,298 kWh and 793 kWh, respectively, are calculated. Statistics for a one-family house constructed after 2016 in Quebec indicate an average heating load of 16,743 kWh for a surface area of 201 m^2 [31]. While specific cooling load data for this vintage are unavailable, the average for a single-family house in Quebec is reported as 704 kWh for a 201 m^2 surface area [31]. These simulated values closely align with the anticipated range of values for the parameters.

3. EAHE impact calculations

3.1. EAHE simulation

Simulations of the EAHE are conducted using the model developed by [36], which is available in the TRNSYS environment as type 460. This model effectively simulates the ducts, air, soil, and interactions between the soil and the surrounding environments.

Most of the space around and beneath the house is filled with undisturbed soil, with only a 0.9 m wide trench around the basement filled with backfill materials (1 m of sand and 1.5 m of gravel). The thermophysical properties used herein for the soil and backfill materials are reported in Table 2.

It's crucial to note that in TRNSYS Type 460, thermal conductivities and surface resistances remain constant over time, which limits the simulation of several phenomena, such as frost within the soil or the presence of snow cover. Moreover, Type 460 cannot model complex geometries. Therefore, the soil beneath the house is simulated using TRNSYS Type 1244. Consequently, Type 460 interacts with three other TRNSYS types: 1244 (soil), 56 (building), and 15 (weather data). Fig. 2 illustrates the link between these components.

Literature suggests that the duct materials have a minimal impact on EAHE performance [11,26,40]. A sensitivity study employing three different materials (PVC, HDPE, and steel) is nevertheless conducted in section 4.4 and extends this claim to the present system. For economic reasons, HDPE ducts are chosen. Thermal properties corresponding to HDPE are sourced from [41] with a thermal conductivity of 0.389 $W.K^{-1}.m^{-1}$ and a specific heat of 1900 $J.kg^{-1}.K^{-1}$.

There are periods during the year when the EAHE could operate in opposition to the house's heating/cooling equipment. For instance, Flaga-Maryanczyk et al. [4] demonstrated that an EAHE was cooling air on certain winter days. To mitigate such occurrences, a simple bypass control is incorporated into the simulation. Control of this bypass relies on the value of the ground temperature around the end of the duct and that of the ambient air that would be drawn into the unit to estimate whether the EAHE will cool or heat the air. By comparing ambient temperature with the temperature inside the building, the simulation determines whether air should pass through the EAHE before entering the house. However, this rudimentary control mechanism is not flawless. There remain instances during the annual simulation where the EAHE operates counter to the house's equipment, particularly when the outdoor air temperature closely matches the building's temperature. However, because the power losses associated are close to negligible and a control using more temperature measurements would be unrealistic in a real system, the control was kept simple.

Table 2
Thermal properties used for ground simulation.

Soil type	Conductivity. ($W.m^{-2}.K^{-1}$)	Volumetric mass ($kg.m^{-3}$)	Specific heat by mass ($J.kg^{-1}.K^{-1}$)
Soil[1]	1.3	2096	963
Gravel[2]	0.872	1838	917.053
Sand[3]	0.976	1787.4	957.09

1: Values for dense, moist soil taken from [37].
2: Values for moist gravel (23% of pores filled with water) taken from [38].
3: Values extrapolated from [39].

3.2. Economic parameters

To evaluate the system's economic performances, the Levelized Cost of Energy (LCOE) will be used. This indicator is calculated using the total annualized cost (C_{tot}) and the annual energy provided (E_{prov}) equation (2) [42]. The total annualized cost is calculated using the investment cost (C_{inv}) and the maintenance cost (C_{maint}) equation (3). The investment costs are annualized using the Capital Recovery Factor (CRF) based on the real discount factor (r_{dis}) equation (4). The real discount factor is calculated from the interest rate (r_{int}) and the inflation rate (r_{inf}) for the whole system's lifetime (*life*) equation (5). To consider in the economic study the greenhouse gas emissions reduction provided by the system, a cost reduction (C_{carb}) will be taken into account. This cost economy will be calculated using the energy provided by the systems, the mean annual carbon content of the electricity grid ($Grid_{CO2}$) and the price of carbon emission (C_{CO2}) equation (6).

$$LCOE = \frac{C_{tot}}{E_{prov}} \tag{2}$$

With:

$$C_{tot} = C_{inv} * CRF + C_{maint} - C_{carb} \tag{3}$$

$$CRF = \frac{r_{dis}(1 + r_{dis})^{life}}{(1 + r_{dis})^{life} - 1} \tag{4}$$

$$r_{dis} = \frac{r_{int} - r_{inf}}{1 + r_{inf}} \tag{5}$$

$$C_{carb} = E_{prov} * Grid_{CO2} * C_{CO2} \tag{6}$$

For the investment cost evaluation, inflation-adjusted values sourced from [16,43] are utilized. Duct unit prices vary based on diameter and are summarized in Table 3. The unit installation cost is determined at 7.66 $US\$.m^{-1}$ [16], the purchase cost of the air inlet module is 383 US$ [16] and the drainage system is valued at 100 US$ [24]. Maintenance costs are estimated using the work of Mostafaeipour et al. considering one annual inspection with air filter replacement for an associated cost of 25 $US\$.year^{-1}$ [44]. The mean annual carbon content of the grid is taken at 31 $gCO_2eq.kWh^{-1}$ for the region of Quebec (Canada) using electricity-map data [45] and the price of greenhouse emissions is estimated at 70 $US\$.tCO_2eq^{-1}$ using the historical price of European Carbon permit [46]. The annualization of cost is conducted with an interest rate of 8 % and an inflation rate of 3.5 %, which gives a real discount rate of 4.35 % [42]. The system's lifetime is considered as 25 years in accordance with the work of Cirillo et al. [12]. The impact of those parameters on results will be studied in section 4.3.

In a typical configuration, an auxiliary fan is required to compensate for pressure losses. For the present study, pressure losses in the tube's length (ΔP_{ducts}) are calculated using equations (7) [47]. The pressure losses are dependent on the Darcy friction factor (f), the length (L) and diameters (D) of the tube, the air velocity (v) and density (ρ_{air}). The Darcy friction factor is calculated using equation (8), using the roughness coefficient (ε), tube diameters and Reynold number (Re) [47]. In

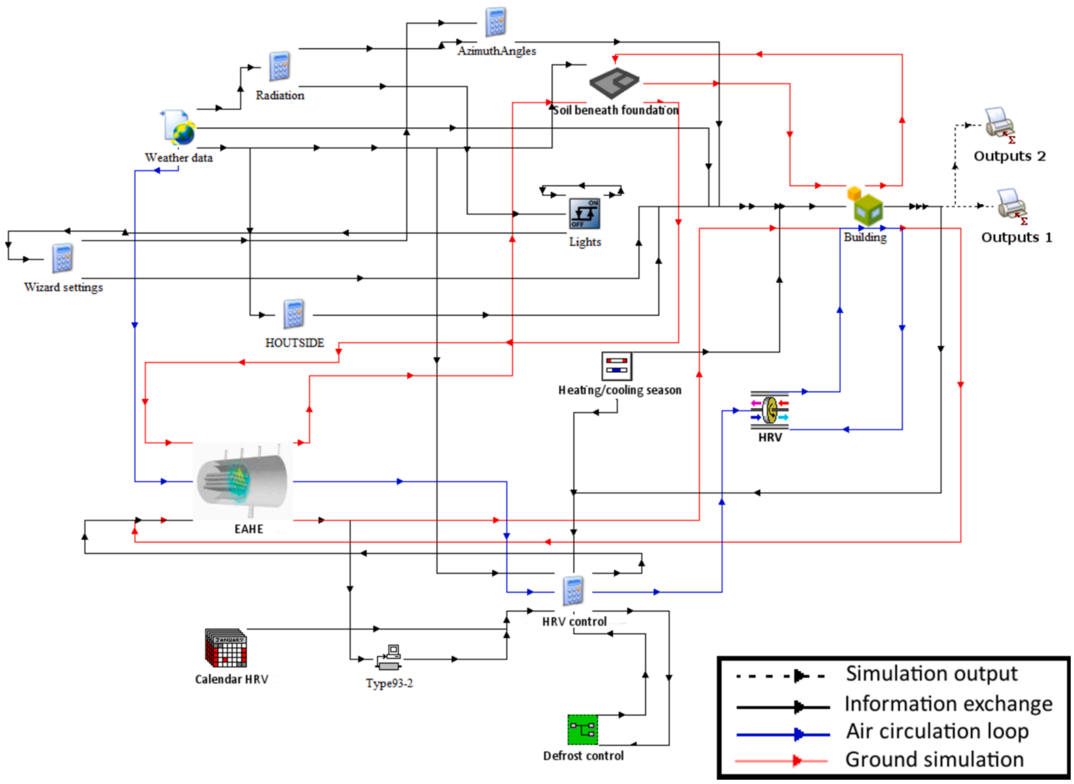

Fig. 2. TRNSYS system representation.

Table 3
Cost of a meter of HDPE pipe by diameter.

Diameter (mm)	200	250	400	500
Price (US$.m^{-1})	17.59	27.29	73.40	115.27

the 6 junctions pressure losses ($\Delta P_{jonctions}$) are calculated with equations (9), using the losses coefficient (K_f) as well as air density and velocity [48]. The losses coefficient is calculated using equation (10) using the tube diameters, Reynold number as well as 3 constant coefficients depending on the junction geometry (K_m, K_i and K_d) [48].

These provide pressure losses ranging from 3.85 to 0.184 Pa for diameters ranging from 0.25 to 0.5 m. Utilizing the performance curve of the HRV [34], at constant electricity consumption, flow rate losses of less than 2.5 % are observed when duct diameters exceed 0.25 m. Thus, an auxiliary fan will not be considered above this threshold, making the systems near passive.

$$\Delta P_{ducts} = f^*\frac{L}{D}{}^*\rho_{air}{}^*\frac{v^2}{2} \tag{7}$$

With:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \tag{8}$$

$$\Delta P_{junctions} = 6^*K_f{}^*\rho_{air}{}^*\frac{v^2}{2} \tag{9}$$

With:

$$K_f = \frac{K_m}{Re} + K_i\left(1 + \frac{K_d}{D^{0.3}}\right) \tag{10}$$

4. Results and discussion

4.1. Sizing

A sizing study was conducted on the system for two primary purposes. Firstly, to identify the configuration that yields optimal results for this specific building, which is subsequently utilized for the economic analysis. Secondly, to obtain several design guidelines from the results, although it's acknowledged that this single study may not necessarily be enough to generalize these guidelines to different buildings. The 4 sizing variables are represented in Fig. 3. The results are presented in Fig. 4 namely for the electricity gain in kWh with respect to: (a) the tube diameter; (b) the EAHE depth; (c) the distance between the EAHE and the foundation wall; and (d) the tube length.

Simulations conducted with various tube diameters (Fig. 4a) show negligible variations as well. For diameters ranging from 0.25 m to 0.5 m, the electricity gain fluctuates by merely 16 kWh annually, corresponding to a marginal 2.3 % improvement when the diameter is doubled. Consequently, for similar mass flow rates of ventilation, smaller diameters appear to be advantageous because of costs and ease of installation. However, it's imperative to consider that smaller diameters induce higher pressure losses. Consequently, the appropriate diameter is determined by choosing the smallest feasible diameter that eliminates the need for a supplementary fan to compensate for pressure losses.

The literature consistently indicates that the deeper an EAHE is buried, the more performant it becomes [11,49,50]. The current results (Fig. 4b) align with this trend. Gains increased by 302 kWh between depths of 1.5 m and 2.5 m, representing a substantial 78 % improvement. However, for a foundation based EAHE, the depth is limited by that of the basement to avoid extra costs. In the current case, excavating deeper than 2.5 m would necessitate additional excavation, so this limiting depth is chosen.

Closer proximity between the duct and the basement wall enhances heat exchange between the two, but may decrease performance due to

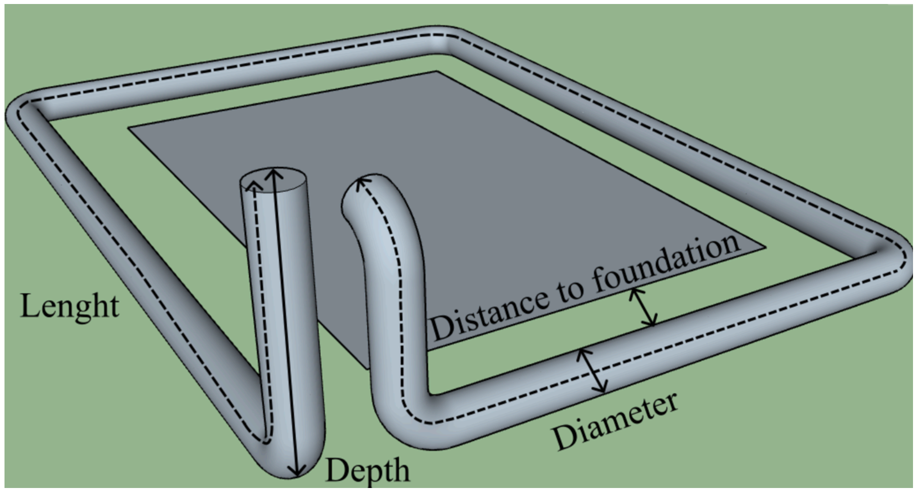

Fig. 3. Representation of the EAHE and the 4 sizing variables.

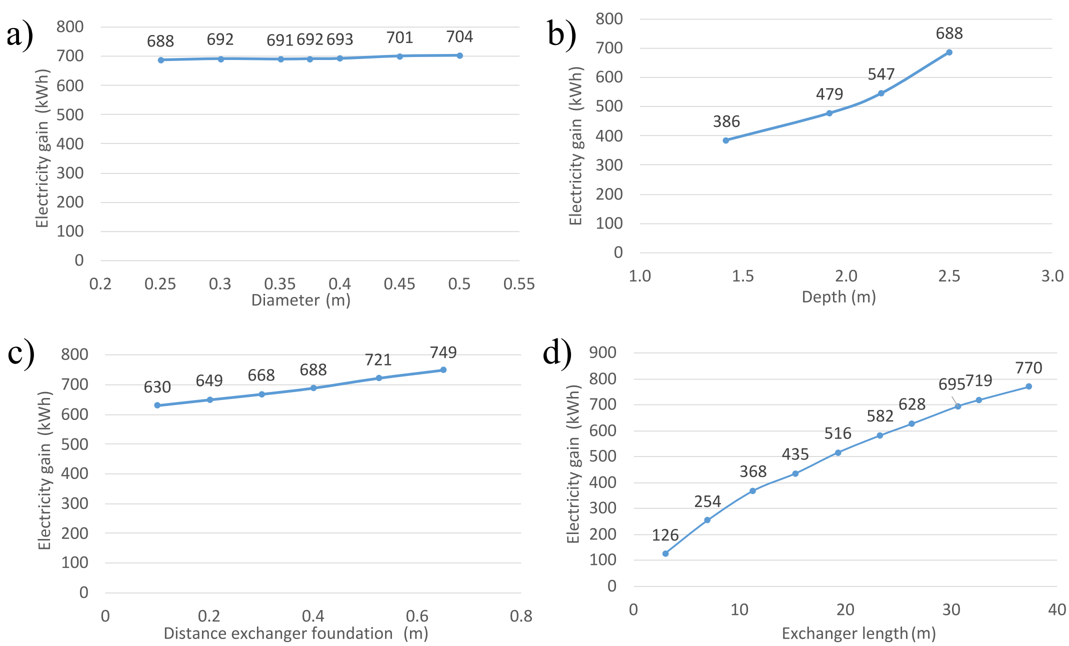

Fig. 4. Performances expressed in terms of electricity gains in kWh as functions off: a) tube diameter; b) tube depth; c) distance of the tube with foundation; and d) exchanger's tube length.

thermal short-circuiting, as highlighted by Hollmuller and Lachal [51]. Results presented in Fig. 4c indicate that increasing the distance from the foundation wall by 0.5 m improves net gains by 14.4 %. Thus, the optimal configuration necessitates maximizing the distance between the two, albeit within the constraints of avoiding extra excavation during installation.

The length of the EAHE is also constrained by available space. Although the maximal length possible with the investigated typical building is 37.3 m, longer lengths incur higher costs. To determine the optimum length, the LCOE is calculated for various lengths, revealing that an EAHE of 31 m provides the best result in our case (Fig. 4d). It's essential to note that the optimal length is dependent on the specific building and economic parameters, such as the price of ducts and installation.

In summary, for this house, the optimal configuration entails a 31 m long EAHE located 2.5 m deep, installed at 0.65 m from the basement wall, and composed of HDPE ducts with a 0.25 m diameter.

4.2. Economic performances

A detailed examination of the configuration proposed in the sizing study reveals that the simulated cooling/heating load of the house with the EAHE around the foundation and coupled with the HRV is 16,390 kWh. By comparing this load with the one simulated without the EAHE, a relatively small gain of 701 kWh is estimated, a mere 4,3% saving. This system's size represents an investment cost of around 1566 US$ and an annualized total cost of 127.5 US$. Readily, the resulting LCOE is 0.182 US$.kWh^{-1}. This is prohibitively high compared to the average domestic electricity rate of 0.059 US$.kWh^{-1} in Quebec, Canada [52]. This initial approximation indicates the limited financial potential for this system in the studied region when coupled with an efficient HRV, as the gain is too low relative to the initial investment, even with a portion of the initial cost (excavation) set aside. This may seem very high, but it should be noted that this equipment is intended to be used for the entire life cycle of the home. An investment of a few thousand dollars, with little or no asset maintenance costs, represents less than half a percent of the total cost of any residential project.

One of the reasons for this low gain is the significance of two types of losses: hereafter, called coupling losses and short-circuiting losses. Coupling losses arise when the EAHE and the HRV operate in series. Essentially, the EAHE reduces the amount of heat recovered by the HRV by decreasing the temperature difference between the fresh air entering the house via the HRV and the exhaust air. The higher the efficiency of the HRV, the more substantial these coupling losses become [51]. Conversely, the EAHE enhances HRV performance by reducing the duration of the defrost cycle (272 h of defrosting without EAHE versus 46 h with EAHE) and improving unit efficiency in the defrosting periods. However, the results indicate that the reduction in temperature difference most of the year has a greater impact than these two phenomena. This suggests that coupling has an overall negative effect on HRV performance.

As mentioned above, short-circuiting losses occur when the EAHE and the building are nearby and the basement heating and cooling load increase because of the close presence of the heat exchanger tube. While heat exchange between the two enhances the amount of heat received/discharged by the air circulating inside the EAHE, a portion of this heat is lost before it can be recovered within the building due to the coupling issues. Both of these phenomena are also observed and discussed in the work of Hollmuller and Lachal [51].

In the optimal configuration, the EAHE receives/discharges 1082 kWh of heat yearly. However, this figure does not directly correspond to the reduction in heating/cooling load due to factors such as coupling and short-circuiting losses. Hence, additional simulations were conducted to assess the HRV's performance, revealing a gain of 4558 kWh without coupling and 4294 kWh when coupled with the EAHE. These simulations estimate coupling losses at 264 kWh. Furthermore, it was determined that the presence of the EAHE around the foundation increased the basement load by 173 kWh.

Out of the 1082 kWh received/discharged by the EAHE: 264 kWh are lost due to coupling between the EAHE and HRV, 173 kWh are utilized to compensate for the increased heating/cooling load of the basement, and consequently, 701 kWh are effectively utilised to reduce the load of the house (Fig. 5). This represents approximately 60 % of the heat received/discharged by the EAHE. The 56 kWh difference between the sum of these three values and the total heat received/discharged by the EAHE could be attributed to unidentified positive effects.

4.3. Economic parameter analysis

The obtained LCOE value is directly influenced by economics parameters chosen. A sensitivity analysis is conducted to observe how the LCOE varies with changes in those parameters. The investment cost of the system is mainly dependent on the duct prices. Fig. 6 illustrates the variation of the LCOE depending on those prices. With prices ranging from 10 to 40 US$.m^{-1} the LCOE varies between 0.13 and 0.22 US$.kWh^{-1}.

The parameters used to annualize the cost also impact the LCOE. Fig. 7 illustrates the variation of the LCOE depending on this real discount rate. The LCOE more than double between a real discount rate of 1 % and one of 10 %. Low interest rates could thus strongly assist in EAHE development and economic viability.

The economic gains associated with greenhouse gas emission reduction also influence the results. This gain is influenced by 2 parameters the electricity grid carbon content and the price associated with emissions. The variation of the LCOE with changes in those parameters is illustrated in Fig. 8. The grid carbon content can greatly vary from one region to another. The average carbon content of the grid is calculated to be around 545 gCO2.kWh^{-1} in Africa, 590 gCO_2.kWh^{-1} in Asia, 344 gCO_2.kWh^{-1} in North America, 259 gCO_2.kWh^{-1} in Latin America, and 490 gCO_2.kWh^{-1} in Oceania [53]. The price of greenhouse gas emissions is not yet well defined. The price of European carbon permits varied between 20 and 100 US$.t$CO_2$eq^{-1} in the last 5 years [46]. Overall, this gain can reduce the LCOE from 0.184 US$.kWh^{-1} to 0.13 US$.kWh^{-1} if a strong emphasis is put on carbon emission penalization.

Finally, in this study, the major contributing factor to the low economic prospect is the relatively low electricity tariff in Quebec compared to other regions of Canada, or even the world. The profitability of the EAHE would be enhanced in regions where electricity or alternative means of heating/cooling are more expensive. For instance, the estimated LCOE is lower than the average Canadian electricity rate (around 0.14 US$.kWh^{-1}).

For reference, the electricity rate among North American cities varies from 0.059 US$.kWh^{-1} in Montréal (Canada) to 0.35 US$.kWh^{-1} in San Francisco (USA) [52]. However, it's essential to recognize that this study utilizes building and economic data derived from the region of Quebec. Therefore, its findings cannot be directly extrapolated to other regions without considering local factors, modifying the typical building performance, etc.

4.4. Energetic parameter analysis

A sensitivity analysis is conducted to observe how the EAHE would perform in other locations. Firstly, changes in ground conductivity from one house to another, while keeping the backfill material unchanged, was investigated. A variation of ± 0.3 W.m^{-1}.K^{-1} in conductivity (23 % of the original value) results in a relatively small impact on the EAHE performance, with a change of 4–6 % (Fig. 9). This highlights the advantages of foundation-based EAHE systems, which exhibit stabler performances across different ground compositions compared to larger-sized systems.

From one city to another, the weather may change drastically, affecting both the building load and the EAHE performances. This is investigated in Fig. 10 for four cities having different climates. However,

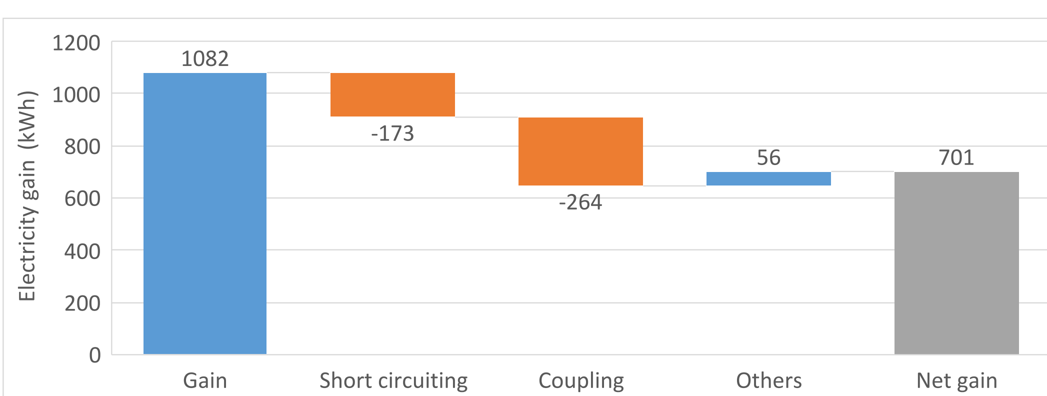

Fig. 5. Waterfall chart of the optimal system performance.

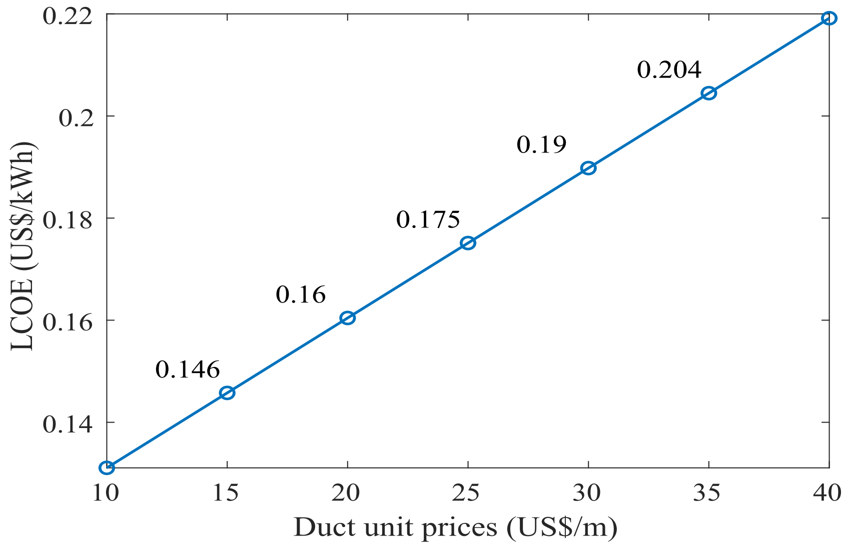

Fig. 6. LCOE variation depending on duct prices.

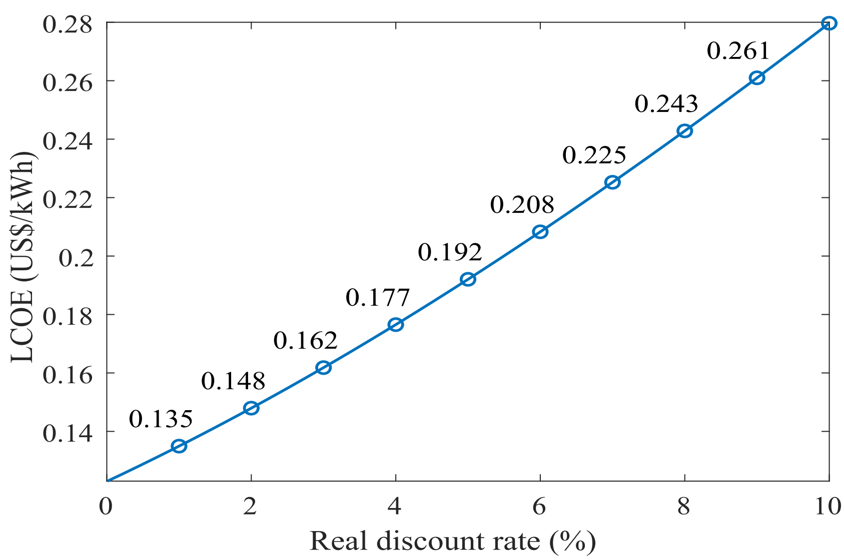

Fig. 7. LCOE variation depending on discount rate.

it is important to note that in all cases, the simulations were carried out with a building envelope that remains the same. Building standards vary significantly from one place to another, notably to account for these weather differences, hence results in Fig. 10 have to be considered in this constant building perspective. Using the Köppen-Geiger climate classification, Montréal and Saguenay are classified as cold climate (Dfb), Seattle and Charlotte as temperate climate (Csb and Cfa respectively) and Miami as tropical climate (Am) [54]. The EAHE gains are reduced in hotter climates. This is related to the higher performances of the cooling system compared to the heating one. In temperate climates the EAHE presents low performances in both heating and cooling due to the small difference in temperature between indoor and outdoor air throughout the year.

As mentioned in section 3.1, the literature indicates that the material used for the ducts has little impact on the exchanger's behavior [11,26,40]. To verify this hypothesis for the present system, the heat exchanger gain is simulated with 3 different materials (PVC, HDPE and steel) using thermal conductivities of 0.19, 0.389 and 49.8 W.K^{-1}.m^{-1} for the PVC [55], HDPE [41] and AISI 1010 Steel [56] respectively. The results are displayed in Fig. 11. The variations between the different materials are very small between 0.4 and 2.2 %. Although the conductivity of steel is almost 130 times greater than that of HDPE, the difference in performance is only 16 kWh. Thus, the literature results extend to the present systems.

Given the significance of thermal short-circuiting losses highlighted in the previous section, the actual use of the basement plays a crucial role in the system's performance. A higher basement heating setpoint, when people use this area as a living area, leads to increased losses due to short-circuiting. For instance, with a setpoint of 10 °C instead of 15 °C, the system's performance improves by approximately 10 % (Fig. 12). Similarly, better thermal isolation of the basement results in reduced short-circuiting losses. A variation of ± 1 m^2.K.W^{-1} (33 % of the original value) in thermal isolation leads to performance changes ranging between 10 % and 25 % (Fig. 13).

Similarly, coupling losses are closely linked to ventilation parameters. Firstly, a higher HRV efficiency results in more energy it can recover for each one degree of temperature difference between the exhaust and inlet air. By reducing the temperature difference, the EAHE thus creates higher negative effects for higher HRV efficiency. Thereby increasing the coupling losses between the two systems and decreasing

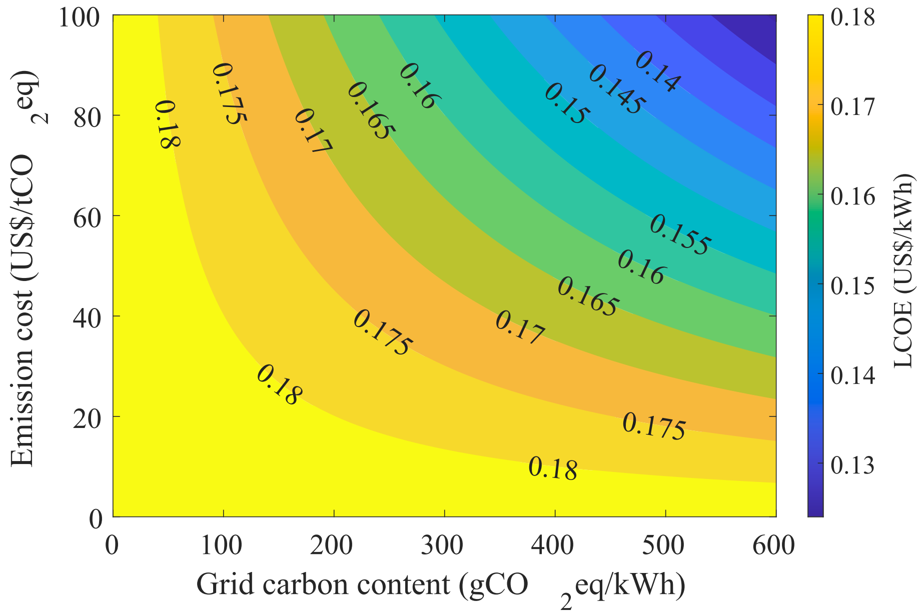

Fig. 8. LCOE variation depending on the grid carbon content and emission price.

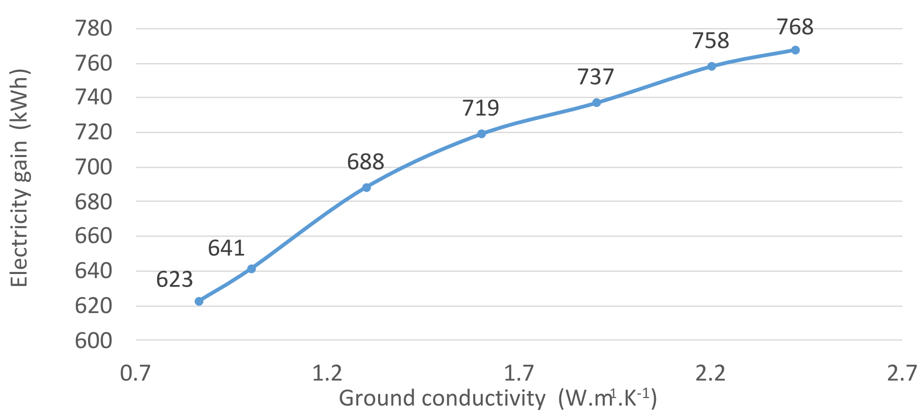

Fig. 9. Performance variations depending on ground conductivity.

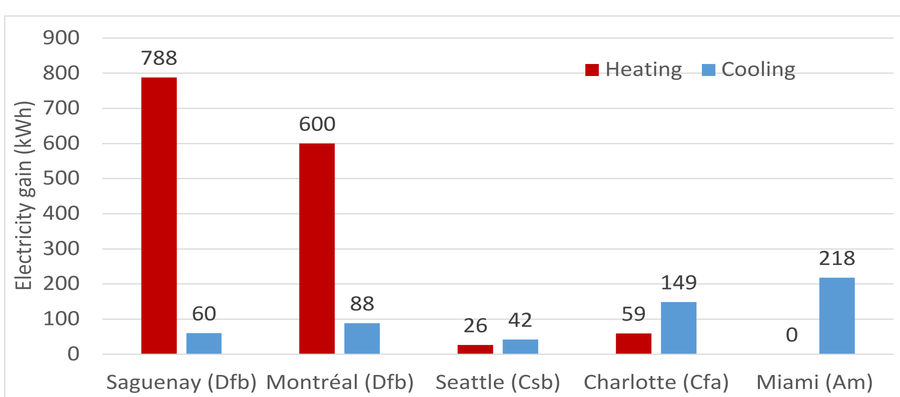

Fig. 10. Energy yearly savings by the EAHE in selected cities in North America with the corresponding climate classification.

the overall EAHE performances. The electricity gain varies with a constant slope of around 780 kWh, so a ± 10 % variation in efficiency will result in a 78 kWh variation in performance coupling losses are closely linked to ventilation parameters (Fig. 14). However, low efficiency HRVs are seldom present on the Canadian market, as the Canadian building code requires HRV to have a minimal efficiency of 54 % at 25 °C to be installed in new residences [28] and thus most HRV on the market have better performance.

On the other hand, an increased ventilation rate significantly reduces these losses. A higher ventilation rate means less heat that the HRV can recover independently. A fluctuation of approximately ± 35 $m^3.h^{-1}$ (equivalent to 20 % of the initial value) results in a shift in the gain,

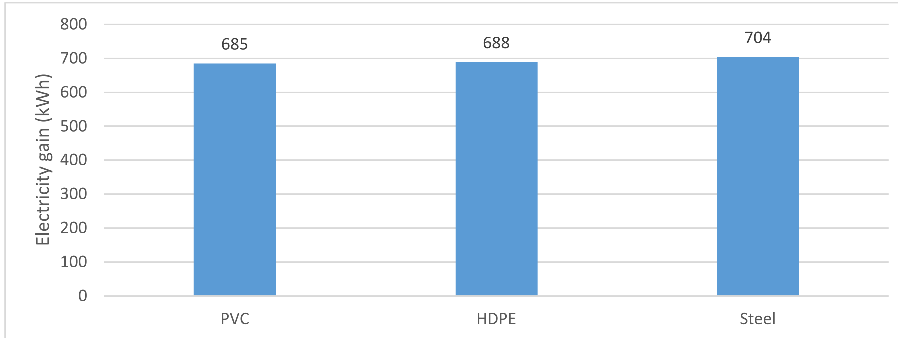

Fig. 11. Performance variations depending on ducts' materials.

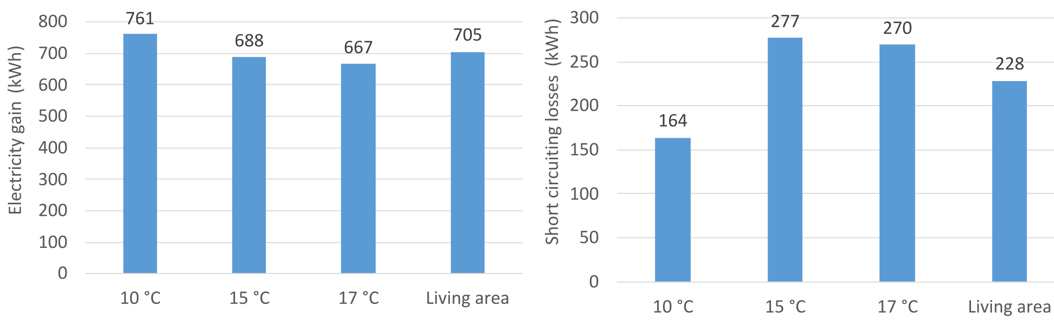

Fig. 12. Performances and short-circuiting losses depending on basement heating setpoint.

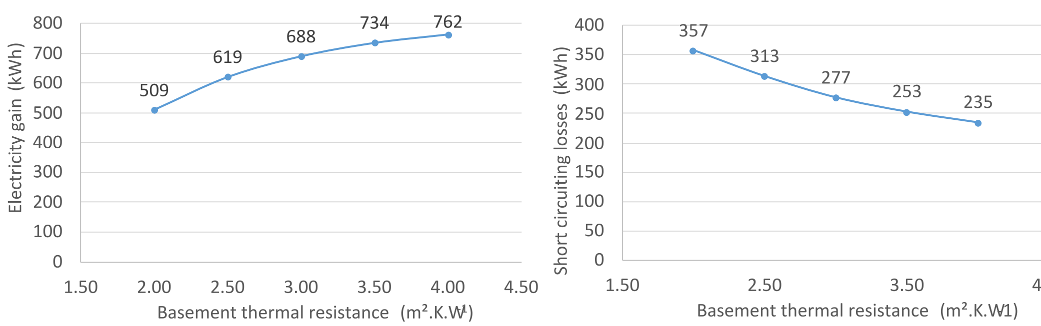

Fig. 13. Performances and short-circuiting losses depending on basement isolation.

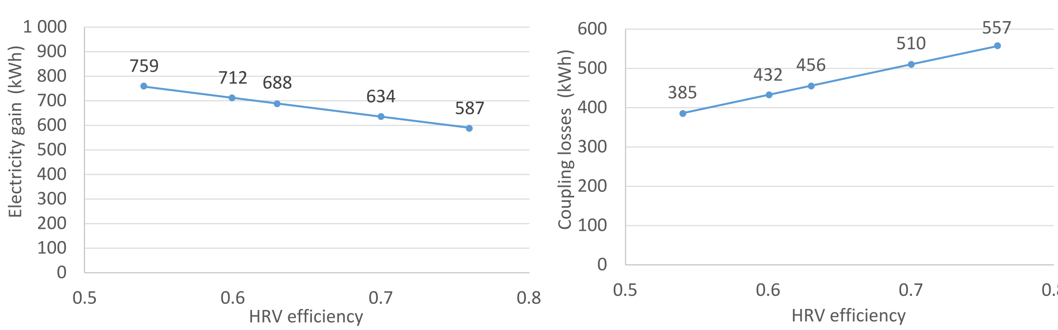

Fig. 14. Performances and coupling losses depending on HRV efficiency.

ranging from 30 % to 60 % (Fig. 15). The curves here are not linear, as an increase in flow rates also means an increase in building ventilation and thus increasing heating consumption. One should note that in cold climates, the flow rate of fresh air is mixed with recirculating air to limit the low temperature of the incoming air. The fresh air debit should vary between 72 $m^3.h^{-1}$ (42.4 CFM or 20 $L.s^{-1}$) in very cold weather and 360 $m^3.h^{-1}$ on warmer days.

5. Conclusion

The objective of this study is to explore the energy efficiency and economic viability of a foundation-based EAHE, a low-tech, near-passive

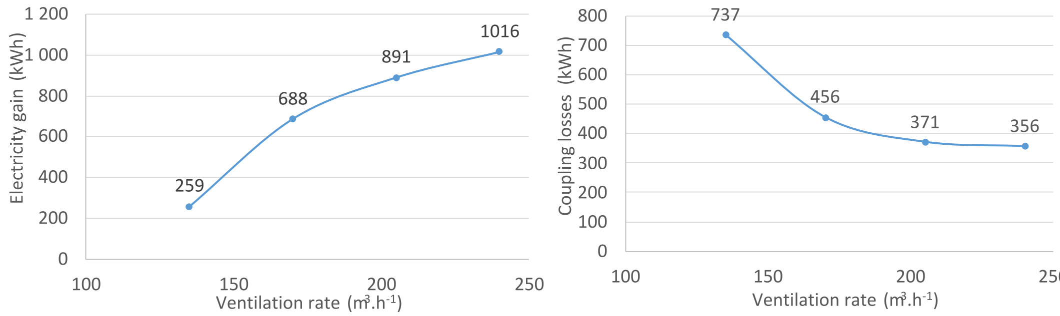

Fig. 15. Performances and coupling losses depending on ventilation rates.

environmental system for reducing heating and cooling loads in individual residential buildings in Canada. This EAHE configuration eliminates the need for additional excavation, since the heat exchanger is installed directly in the excavation required by the building foundation during construction. This results in lower overall costs but constrains the available space and thus the system's performance potential. In Canada, as HRVs are mandatory, the proposed EAHE was coupled linearly with the device.

Numerical simulations were conducted to evaluate the combined performance of the EAHE system, the building, and an HRV, with attention focused on understanding their interactions. The study emphasizes the significant impact of short-circuiting losses (between the foundation walls and the exchanger) and coupling losses (between the exchanger and the HRV) on the technology's performance. Understanding and addressing these losses are crucial for accurate sizing, as they account for more than a third of the total heat received/discharged by the exchanger in the typical case.

More specifically, the following points can be mentioned:

- The material of the ducts has a minimal impact on performance.
- The EAHE should be located as deep and as far away from the basement as possible, without requiring additional excavation.
- Smaller tube diameters show better economic potential, but attention should be paid to the pressure losses induced by the EAHE. The smallest diameter should be selected without necessitating an additional ventilator due to increasing pressure drops.
- Short-circuiting losses occur when the EAHE is close to the basement walls, while coupling losses occur when the EAHE is coupled with an HRV. Both types of losses are non-negligible, and their behaviors need to be considered in sizing.
- Short-circuiting losses are deeply linked to the basement usage and its thermal isolation.
- Coupling losses are deeply linked to the HRV efficiency and the building ventilation rate.
- This configuration of EAHE performs similarly across different soil types.
- Given the calculated LCOE of 0.182 US$.kWh^{-1}, the study indicates limited potential for the system in regions with low electricity rates and mandatory HRV on new constructions, such as Southern Quebec (Canada).

The preponderant conclusion of the study is that the use of EAHE in the Quebec context is interesting from an energy point of view despite the above-mentioned financial drawbacks. It would require legislation to force constructors to install it. Otherwise, energy rates will need to increase a lot to financially justify such equipment.

The study contains several limitations, which could make ground for future research. Firstly, the study relies mostly on simulation results which could be improved with experimental data from experimentation in situ. The convection heat transfer inside the ducts is calculated using an analytical model based on experimentation [36]. A full computation of the airflow inside the ducts would improve the results precision. However, this would also significantly increase computing time. The defrost cycle of the HRV is of importance to the present study because the earth air heat exchanger (EAHE) provides an indirect energy gain by reducing the time the HRV spends defrosting itself. However, only one defrost method was here considered. Studying the performances with HRVs using different defrost methods would allow to better understand how much energy the EAHE provides. Only one building envelope and building type were considered. Thus, reproducing the simulation with different building types and envelopes could be of interest, especially in regions with high heating and cooling costs. The freezing of the soil and snow cover can influence the results and was not taken into account, adding this phenomenon could improve the simulation precision for the coldest climates. The EAHE model can only simulate one tube coiling once around the house. Studying configurations with multiple ducts coiling multiple times around the foundation could bring interesting results. However, in this case the temperature of the soil between the ducts must be meticulously modelled. To limit the scope of the current study, only cases with no additional excavation were considered. As the excavation equipment is already on-site during foundation construction addition excavation to increase the EAHE length could be made at a low cost. A holistic optimization of the system was not conducted. However, this type of study could improve the system's performance even more so in the case where extra excavation, coiling or ducts are considered because the design space significatively increases.

CRediT authorship contribution statement

Mathieu Patin: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel R. Rousse:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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