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Potential Applicability of Earth to Air Heat Exchanger for Cooling in a Colombian Tropical Weather

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Abstract: Buildings exhibit a high energy consumption compared with other economic sectors. While percentages vary from country to country, buildings are responsible for approximately 40% of the global energy demand. Most of this is consumed for achieving human thermal comfort. In Colombia, the government promotes policies for the adoption of efficient energy strategies in this sector. The earth to air heat exchanger (EAHE) can be used to reduce the cooling load of a building. Therefore, this study aims to evaluate the energy savings that can be obtained by installing an EAHE in a tropical climate in Colombia. To do so, a mathematical model is implemented in TRNSYS (Transient System Simulation Tool) to predict the thermal performance and the cooling capacity of the EAHE. The system is modeled as a function of pipe length, diameter, material, thickness and air mass flow. Moreover, soil, local atmospheric conditions and building features are taken into account. It is found that the air leaves the EAHE at temperatures between 20.9 °C and 24.1 °C, which are approximately 3 °C below ambient temperature. Furthermore, the economic feasibility of the project is verified. Thereby, it is demonstrated that the EAHE can be a competitive alternative to current HVAC systems.

Keywords: passive cooling; EAHE; temperature potential; ventilation; TRNSYS; soil temperature

1. Introduction

Energy supply is fundamental for the economic development and the well-being of the population of any country. Furthermore, energy consumption has increased considerably due to growing needs to ensure thermal comfort conditions inside buildings [1]. For this reason, the achievement of indoor thermal comfort while minimizing energy consumption in buildings is a crucial aim around the world. Therefore, during the last decade, there has been a rising interest in implementing alternative sources to replace conventional cooling of buildings [2–4]. In Colombia, about 70% of energy generation is obtained from hydropower. Consequently, the Colombian electricity sector is highly vulnerable to sufficient water availability [5]. For instance, during 2015 and 2016, the droughts suffered in this country as a result of the natural phenomenon called “El Niño” were close to causing a blackout due to the drop in the electricity generation of the hydroelectric plants [6]. For this reason, governmental and non-governmental entities are promoting policies to diversify energy sources. They are taking measures oriented to new generation systems and management of demand, especially in those areas with a high level of energy consumption, such as cooling of buildings [7].

One of the promising passive cooling techniques is Earth to Air Heat Exchanger (EAHE). It takes advantage of the fact that ground temperature, at a certain depth, is almost constant throughout the year. This allows its use as a heat sink. EAHE consists of a simple system of buried pipes through which ambient air circulates. Therefore, part of the thermal air energy is transferred to the ground during this movement. Then, the outlet air from the EAHE can be directly used for space cooling or as pre-cooled air in an HVAC system [2,8,9]. The degree of success of the EAHE depends on many parameters, for instance, local atmospheric conditions such as solar radiation, ambient air temperature and...
relative humidity, as well as design aspects of the heat exchanger: Configuration, depth of burial, air flow rate, pipes diameter and length [10–12].

In the last decade, many studies have been done on EAHE configurations to analyze its energy performance. Results showed that EAHE is an energy-efficient system that can be used to achieve thermal comfort inside buildings. Lee and Strand [13] evaluated the cooling and heating potential of earth tubes in four representative locations in the U.S. They created a mathematical model for EAHE in an Energy Plus software environment. A detailed algorithm was used to calculate the soil temperature variation for each pipe for every time step of the simulation. Moreover, Ascione et al. [14] studied the energy performances achievable using an EAHE in different Italian climates. This work showed that the best performance of the EAHE system can be obtained with a pipe length of 50 m, buried 3 m deep in wet soil. Benhmammou and Draoui [15] developed a one-dimensional transient model to study the thermal performance of EAHEs for air cooling in summer in the Algerian Sahara Desert. Their results revealed that the daily mean efficiency increases when the length of the pipe does, but it decreases when the cross-section area of the pipe or air velocity is reduced. Shojaei and Malek [16] evaluated the potential energy savings of a four-pipe EAHE for different climates of Iran. Their findings indicated that the average energy savings changes according to the weather in the analyzed cities. Furthermore, the EAHE shows better behavior when the soil is silt, in comparison with loam and clay soil.

In this sense, several researches have evaluated the EAHE performance in different locations. These works have demonstrated that the EAHE can provide excellent thermal comfort and indoor air quality, with low energy consumption. Despite their general good performance, EAHE efficiency depends on local atmospheric conditions and soil characteristics. For this reason, it is important to evaluate the EAHE considering local features [8,13–15,17]. Moreover, there is a lack of this kind of research in tropical climates, where the amplitude of the soil temperature wave is smaller. As a consequence, in tropical regions the attenuation of the temperature also occurs in the most superficial layers [18,19]. Therefore, the purpose of this study is to evaluate the performance of an EAHE in a Colombian tropical weather in terms of ambient air-cooling capacity. This is done by means of the modelling of the system in TRNSYS. Furthermore, the present study focuses on the simulation of an EAHE system designed to improve thermal comfort in a laboratory room. The space is also simulated using TRNSYS. The laboratory is located in the Mechanical Engineering School building at Universidad Industrial de Santander (UIS), Bucaramanga, Colombia.

While experimental validation is required to ensure the effectiveness of possible enhancements, the use of simulation tools allows a better understanding of the system and its performance under different operation conditions. Nowadays, detailed simulation models are becoming more important in the design phase. TRNSYS software is commonly used to study this kind of system. Libraries of this numerical tool have been verified in various studies. Moreover, it has demonstrated to be a very useful tool for analyzing and optimizing the performance of EAHE in different types of constructions, including offices, hospitals and residential buildings [20–25].

This document starts by describing the local weather, soil characteristics and building construction details considered for the EAHE design and evaluation. Afterwards, the process carried out for the parametric analysis, thermal loads estimate, coefficient of performance evaluation and financial analysis is explained in the methodology section. Then, results and discussion are presented to show the relevant findings of this work. Finally, the conclusions are outlined.

2. Description of Study Case

2.1. Local Weather Conditions and Soil Characteristics

Weather conditions are measured by a Vantage Pro2 weather station installed at the Mechanical Engineering School building in the Universidad Industrial de Santander (UIS), Bucaramanga, Colombia (7° 8’ 23.604” N; 73° 7’ 15.204” W). For the location, there are two
rainy seasons, from March to May and September to November. Moreover, there are two dry seasons, from December to February and June to August. The annual air temperature was measured during 2017; it varied from 20.9 °C to 31.3 °C. The mean annual air relative humidity was 80%, with a minimum of 49%. Figure 1 shows an example of the measured data corresponding to the second week of January, right in the middle of the dry season from December to February. Furthermore, the mean annual solar radiation was 700 W/m². The rainfall varied from 1 mm to 3 mm per day during rainy and dry seasons, respectively.

![Figure 1. Example of measured relative humidity and air temperature for a given week.](image.png)

Because soil characteristics and its temperature variation are some of the main concerns in EAHEs, an electronic tool is designed to measure the temperature and moisture content of soil for the location (see Figure 2). It has seven sensors for measuring underground soil temperatures and moisture. The sensors are located 0.5 m from each other between 0 and 3 m depth. The device is situated in the place where the EAHE will be located (7°08’21.6” N; 73°07’12.8” W). All temperature sensors are calibrated against a Cole Parmer Polystat Standard 1-C6 bath, which has an accuracy of ±0.01 °C according to its calibration certificate. Each sensor is tested 20 times for six temperatures: 15, 17, 19, 21, 23 and 25 °C. Observed accuracy is below 1%.

![Figure 2. Temperature and humidity measurement device.](image.png)
Furthermore, to calibrate the volumetric water content (VWC) sensors, eighty samples of ground are taken from the ground. This ground is dried for 24 hours in an oven at 120 °C. Then, each sample is prepared with a VWC from 1% to 40% with a step of 1%. Each sensor is tested three times for each VWC value. All sensors show a saturation point at about 28% VWC. The fitting is performed for each sensor with $R^2$ greater than 99% and it is represented by this equation:

$$VWC = 339,314,287 - 315,950,014 \times h + 0.013089055 \times h^2 - 0.0000282115481 \times h^3 + 328,761,590 \times 10^{-8} \times h^4 - 195,409,715 \times 10^{-11} \times h^5 + 460,914,550 \times 10^{-15} \times h^6$$ (1)

where $h$ means data read by the DAQ, i.e., an integer number from 0 to 1024 due to the DAQ number of bits. The test performance after calibration for each sensor is shown in Appendix A.

Temperature and soil moisture content data are measured with an interval of 15 min during the most representative weeks for rainy and dry seasons, respectively. Additionally, it is known that soil temperature is influenced by the physical properties of the ground, i.e., porosity, permeability and texture. Furthermore, each soil type has a different thermal conductivity depending on its VWC. Sand with high VWC has a high thermal conductivity. Nonetheless, soils that have a high content of clay or organic materials like shale or coal have low thermal conductivity. For this reason, a sample for each depth is taken and a laboratory texture test is performed (see Figure 3).

![Figure 3. Samples taken for a laboratory texture test.](image)

2.2. Building Details

Generally, the main source of energy consumption in a building is the cooling demand in a hot climate. This principally depends on the construction materials, the envelope and the glazed surfaces. Other significant factors that influence the building loads are the occupancy and the internal sources of heat such as lights or electrical appliances. Because of the space available to install the EAHE, only one space inside the building is considered: The Design Laboratory in the Mechanical Engineering School building at Universidad Industrial de Santander (UIS). For this room, all the heat sources and architectural characteristics are taken into account (see Figures 4 and 5).
are the occupancy and the internal sources of heat such as lights or electrical appliances. Because of the space available to install the EAHE, only one space inside the building is considered: The Design Laboratory in the Mechanical Engineering School building at Universidad Industrial de Santander (UIS). For this room, all the heat sources and architectural characteristics are taken into account (see Figures 4 and 5).

Figure 4. Building front view, Design Laboratory highlighted.

Figure 5. Building top view, Design Laboratory highlighted.

Geometrical modeling was done on TRNSYS 3d plug-in for google SketchUp to draw the Design Laboratory with the following dimensions: 7.82 × 21.55 × 3.075 m³. The model includes the geometry in conjunction with architectural parameters such as windows, shelters, doors and walls. Then, the energetic model was generated on TRNSYS Building frontend (TRNBuild). The building model was imported into TRNBuild to calculate the cooling load (see Figure 6).
For this purpose, the masonry, structural elements, envelope materials and architectural details were considered. The thermo-physical properties of each one of the considered components were included.

The Design Laboratory has occupant capacity for 26 people. The scheduling occupancy, lights and appliances operation of the Design Laboratory were estimated according to ASHRAE Fundamentals [26] and ASHRAE standard 90.1 [27]. Furthermore, infiltrations and ventilation requirements were set according to the same source. Table 1 presents a summary of the main parameters used in the energetic modelling for cooling load calculation. Furthermore, building characteristics regarding construction materials and envelope are summarized in Appendix B.

Table 1. Space parameters for cooling load calculation.

| Parameter               | Value                                      |
|-------------------------|--------------------------------------------|
| Location of building    | The second floor of Mechanical Engineering School |
| Application             | Design laboratory                          |
| Building area           | 169 m²                                    |
| T°C Setpoint            | 24 °C                                     |
| Number of people        | 26                                        |
| Light                   | 3.69 W/m²                                  |
| Equipment               | 1080.58 W                                 |
| Infiltration            | 0.2 m³/s                                   |
| HR (low-level limit)    | 50%                                        |

Moreover, to verify the results observed from the simulation carried out in TRNSYS, air temperature was measured in the modelled space. An illustrative comparison between simulated and experimental data is presented in Figure 7. This time segment was chosen...
to illustrate the comparison between experimental and predicted temperature. As can be seen, a difference of about 8% was achieved.

![Figure 7](image-url)  
**Figure 7.** Illustrative comparison between experimental (green solid line) and predicted air temperature inside the studied space (black solid line).

**3. Methodology**

**3.1. EAHE Cooling Potential: Parametric Analysis**

A TRNSYS model was set up to simulate the heat transfer process. The EAHE subroutine, Type 997, simulated the thermal interaction between the buried heat exchanger and the ground (see Figure 8). Boundary conditions were established according to the measured soil properties. Furthermore, operating parameters were set to obtain the outlet air temperature [18]. Additionally, weather data from Vantage Pro2 station were acquired through Type 99. Then, this Type provided them to Type 997 (see Figure 8).

A full description of the model is reported in TESS documentation. The main type, Type 997, was fine-tuned to capture the physical, geographical and climatic characteristics of the site. The simulations were performed with a PVC pipe (thermal conductivity equal to 0.185 W/m·K) buried at 1.5 m from the surface to evaluate the performance of EAHE. The simulation tests were conducted using a pipe length of 60 m, a diameter of 8 in (0.2 m) and a mass flow of 1240 kg/h as reference. However, one of these three design parameters was varied for each of the simulation tests while the others remained constant. The design parameters examined were mass flow rates of 620, 1240 and 1860 kg/s. Pipe diameters were 4 in (0.1 m), 8 in (0.2 m) and 12 in (0.3 m). Pipe lengths were 90, 150, and 200 m, varying each parameter independently.

The influence of grid parameters, such as the node size, node growth multiplier or the relationship factor between the cylindrical node and square node on the EAHE outlet air temperature, was verified.
The EAHE’s operating mode was in continuous mode. Therefore, Type 112 also operated in continuous mode. It has an ON/OFF control which is described as follows: If the input control signal to the fan is less than 0.5, then the fan is OFF. On the other hand, if it is equal to or greater than 0.5, the fan is ON.

3.2. Coefficient of Performance

The coefficient of performance ($COP$) of the system was evaluated using Equation (2) within the TRANSYS environment. In this equation, $COP$ is the coefficient of performance, $m$ is the air mass flow rate through the pipe, $C_d$ is the pipe discharge coefficient and $c_p$ is the air specific heat capacity. Furthermore, $Q_i$ is the work done by the blower and $T_{inlet}$ and $T_{exit}$ are the air temperatures at the EAHE inlet and outlet, respectively. The $COP$ indicates the energy efficiency of the system [28]. The EAHE cooling potential is evaluated based on the analysis of the daily $COP$. The cooling load is calculated by TRNSYS subroutine, Type 56. This is carried out as reported in Multizone Building modeling [29].

$$COP = \frac{mC_d c_p (T_{inlet} - T_{exit})}{Q_i}$$ (2)

3.3. Financial Analysis

There are several economic exploration techniques. Two of them were used in this study: Net present value (NPV) and internal rate of return (IRR) [30]. These analyses consider the initial capital, operations, savings and associated costs. The initial capital or investment includes: Heat transfer subsystem, air distribution subsystem, centrifugal fans, ductworks and borehole excavation. The operation costs involve electricity consumption and maintenance of the EAHE. The savings include the air conditioning system (AC) and its inherent electricity consumption. The EAHE and AC investment cost are obtained by a
detailed unit price analysis. The equipment, material and labor prices are provided by the local industries.

Furthermore, an economic analysis was completed based on some necessary assumptions: Inflation rates are ignored, as well as the annual increase of cost by electricity consumption. Moreover, a discount rate of 8% which applies in Colombia [31] and the lifespan of the EAHE equal to 25 years were evaluated.

4. Results and Discussion

4.1. Soil Temperature and Volume Water Content

Results in Figure 9 show that the lowest temperature of 19.6 °C was obtained just below ground surface (0 m depth). However, it is strongly affected by the ambient temperature and humidity [32]. The heat exchange of the ground surface with the ambient is due to convection with the air and radiation with the sky. It also receives solar irradiation during daytime.

Deeper ground layers experience fewer variations in temperature and the changes exhibit a larger time delay than those of shallower soils. This is caused by the high thermal inertia of the soil under the surface of the earth [33]. While the temperature increases with depth, its fluctuation between day and night reduces. Deeper samples can be considered as a heated basin [19].

Therefore, for the present study, the EAHE would be buried at 1.5 m depth. Here, temperature and its amplitude remained almost constant at 22.3 °C during the testing period (see Figure 9).

Regarding the VWC, measurements show that near the surface (0 and 0.5 m) it is affected by atmospheric conditions. However, when depth increases, the VWC is more constant. On average, it is 25% at 1.5 m depth (see Figure 10).
Results indicate that the soil in the EAHE location is composed of 57.6% sand, 12.4% limestone and 30% clay. Soil thermophysical properties were estimated according to textural properties as follows: Thermal conductivity 2.42 W/m·K, volumetric heat capacity 2.9 MJ/m³·K, specific heat capacity 1.45 kJ/kg·K and thermal diffusivity $0.83 \times 10^{-6}$ m²/s [34–36].

4.2. EAHE Cooling Potential: Parametric Analysis

Different simulations are conducted using fixed design parameters while one of them is varied for each of the simulation tests. The first simulation evaluates the influence of the mass flow rates of 620, 1240 and 1860 kg/h. These values correspond approximately to 1, 2 and 3 ACH (Air Changes per Hour), respectively, for a design laboratory of 510 m³ according to ASHRAE-62.1 [30].

As can be seen in Figure 11, the simulated EAHE air outlet temperature followed the variations of the ambient outdoor air temperatures with a minor amplitude. The ambient air temperature range was 19.1 °C to 27.8 °C in January, while the simulated outlet air temperature was 22.1 °C to 23.7 °C for 620 kg/h, 21.5 °C to 24.3 °C for 1240 kg/h and 21.1 °C to 24.8 °C for 1860 kg/h.

Furthermore, the outlet air temperature increased when the airflow rate inside the EAHE increased. Similar results were obtained by other authors [10,34]. This behavior can be explained because a higher mass flow with the same diameter implies a higher velocity of the air inside the tube. Consequently, the overall heat exchange was reduced owing to the minor residence time of the air inside the pipe [14].

Once the influence of the mass flow was stated, the performance of EAHE was evaluated with a constant tube diameter of 8 in (0.2 m) and operated with an air mass flow rate of 1240 kg/h for three different pipe lengths (90, 150 and 200 m). Again, the EAHE outlet air temperature varied according to the ambient temperature. However, while ambient temperature fluctuated between 19.5 °C and 27 °C, the EAHE air outlet temperature for 90 m pipe length varied from 21.6 °C to 24 °C. For 150 m pipe length, EAHE air outlet temperature varied from 22 °C to 23.3 °C, and for 200 m pipe length, it varied from 22 °C to 23 °C (see Figure 12).
temperature varied from 22 °C to 23.3 °C, and for 200 m pipe length, it varied from 22 °C to 23 °C (see Figure 12).

Thereby, it can be observed that an increase in the pipe length results in a decrease in the variations of outlet air temperatures. Thus, peaks of the air temperature during the day are reduced. These results are similar to those reported by [10,12,34]. Finally, the influence of the tube diameter was evaluated, i.e., 4 in (0.1 m), 8 in (0.2 m) and 12 in (0.3 m) are considered.

For these simulations, a pipe length of 60 m, buried at 1.5 m depth with an air mass flow rate of 1240 kg/s, was imposed. As Figure 13 shows, the outlet air temperature for

Figure 11. EAHE outlet air temperature vs air mass flow rate.

Figure 12. EAHE outlet air temperature vs pipe length.

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For these simulations, a pipe length of 60 m, buried at 1.5 m depth with an air mass flow rate of 1240 kg/s, was imposed. As Figure 13 shows, the outlet air temperature for
a 4 in (0.1 m) pipe diameter varied from 21.1 °C during the night to 24.8 °C in the day, whereas it changed from 21.5 °C to 24.3 °C for 8 in (0.2 m), and from 21.6 °C to 24.3 °C for 12 in (0.3 m).

For these simulations, a pipe length of 60 m, buried at 1.5 m depth with an air mass flow rate of 1240 kg/s, was imposed. As Figure 13 shows, the outlet air temperature for a 4 in (0.1 m) pipe diameter varied from 21.1 °C during the night to 24.8 °C in the day, whereas it changed from 21.5 °C to 24.3 °C for 8 in (0.2 m), and from 21.6 °C to 24.3 °C for 12 in (0.3 m).

Therefore, an increase in the pipe diameter from 8 in to 12 in had a rather limited influence on the outlet air temperature fluctuations.

In summary, it is considered that the best combination of EAHE design parameters to get an outlet air temperature varying between 21.1 °C and 24.3 °C is: 8 in (0.2 m) diameter, 150 m length and air mass flow of 1240 kg/h.

However, for the Design Laboratory, an air mass flow of 1240 kg/h would allow only 2 air changes per hour (ACH), but according to ASHRAE [30], 2.6 ACH are required. Moreover, if the air mass flow increases so does outlet air temperature. Alternatively, the air mass flow and pipe length can be increased simultaneously without affecting the EAHE outlet air temperature, while ACH is improved.

For this reason, the EAHE is designed as a network of buried pipes that has seven tubes of 36 m length (a fan for each one), a diameter of 8 in (0.2 m) and an air mass flow rate of 1560 kg/h in continuous operation mode. The simulated results for the last 1000 h of one year are presented in Figure 14. As the figure shows, the continuous operation strategy takes advantage of night cooling.

During night hours, ambient air temperature goes down and cools the soil, which allows it to recover its cooling capacity [2,37]. The thermal performance analysis reveals that the outlet air mean temperature is 22.5 °C and varies between 20.9 °C and 24.1 °C (see Figure 14).

Hot air peaks are suppressed in this way. The results obtained in this work agree with the study reported by Díaz-Hernández [37] for an EAHE under similar weather conditions.
4.3. Coefficient of Performance (COP)

The COP was calculated using TRNSYS software. The model incorporated the climatic data (Type 99), the behavior of soil (Type 997), operating conditions (Types 56 and 997) and building details (Type 56). Variations in COP depended on soil temperature. When the ambient air temperature was higher than the soil temperature, the air released heat to the soil. In this manner, the EAHE air cooled down space. This cooling effect took place from 9 am to 8 pm.

On the other hand, at night, from 8 pm to 9 am, the soil temperature was higher than the ambient air temperature and heat flowed from soil to air. The weekly maximum cooling COP was around 160 and the daily variations of COP were found in a range between 0.91 and 160.

The high value of the COP and the parallel distribution of the EAHE allow energy savings compared with a standard HVAC system. Low power consumption fans (0.12 kW for the motor) installed in each pipe could be used to vary the operation mode for future research on wet soil conditions [33]. When a low cooling potential is required, some fans could be turned off to increase the COP. The magnitude of calculated COP values is similar to typical values found in the literature and reflect the high efficiency of the heat exchanger [38].

4.4. Financial Analysis

Figure 15 illustrates the instantaneous energy load calculated. The heat was transmitted in or out of the laboratory mainly through external walls, windows, doors and ceiling. Moreover, some heat was transmitted through the floor. Total heat load is the summation of the sensible heat with the total latent heat.
Figure 15. Total heat transfer obtained from TRANSYS model.

The energetic model allows the calculation of air conditioning capacity. According to the analysis, 95% of occupancy hours can be satisfied with a cooling capacity of 10 refrigeration tons RT (35.168 kW) which satisfies the requirements of 300 unmet load hours of the ASHRAE standard 90.1 [27].

In this section, the HVAC system costs associated with maintenance, energy consumption and the initial investment are compared to the costs of the EAHE construction and operation. The EAHE and HVAC investment were calculated using a detailed unit price analysis during the year 2019. Furthermore, equipment, material and labor prices were provided by the local industry. Table 2 summarizes the cost of the EAHE and the HVAC systems. The maintenance and energy consumption costs are evaluated annually. However, the investment of the project is only considered for year zero.

Table 2. EAHE vs. HVAC costs.

| Cash Flow                        | EAHE       | HVAC       |
|----------------------------------|------------|------------|
| Investment cost ($)              | US$23,825.40 | US$6338.02 |
| Maintenance cost ($)             | US$524.62  | US$139.75  |
| Electricity consumption cost ($/annual) | US$1111.92 | US$5678.76 |

The cash inflows are all costs of HVAC; they are incomes. The cash outflows are all costs of EAHE; they are losses. The energy consumption of the HVAC represents the largest portion of the total operational cost. Cash flow was calculated in TRNSYS and considered: Cooling schedule setup point and occupancy schedule, cooling capacity of the air conditioner, operation mode, frequency of use, the electricity tariff in Bucaramanga and its weather conditions.

Moreover, the maintenance cost for the mechanical system and civil construction is about 3% of the total investment cost for each one [39]. These cash flows are added in each year of the overall analysis period, resulting in an NPV calculated equal to US$25,662.3. Then, applying the criteria of NPV > 0, a positive value means that this project is a rentable
way to invest the money. On the other hand, the internal rate of return is calculated as 23%. The interest rate obtained is higher than bank interest rates, and payback time is archived in approximately six years, which, from a basic financial point of view, makes the project profitable.

5. Conclusions

The technical and financial feasibility of an EAHE installed in tropical weather in Colombia to acclimatize a laboratory inside the Mechanical Engineering School (UIS) building at Bucaramanga was analyzed. To do so, the EAHE and the laboratory were simulated using TRNSYS. Moreover, to provide inputs for the model, the temperature, the volume of the water content and thermophysical properties of the soil were experimentally obtained.

Furthermore, local weather conditions were measured. Regarding technical aspects, an EAHE with a length of 252 m (7 pipes in parallel) and a pipe diameter of 8 in (0.2 m) produced the best results. Furthermore, an air mass flow rate of 1560 kg/h provided enough air exchanges per hour without reducing the EAHE performance while satisfying calculated thermal loads. With these dimensions and operating conditions, the EAHE delivered air at temperatures between 20.9°C and 24.1°C, which are within the established conditions of thermal comfort. For the calculated specifications, the project had an IRR of 23% and a payback period of six years. Therefore, the project is considered financially viable. The EAHE could also be implemented in tropical areas with similar atmospheric and soil conditions to increase the thermal inertia of the buildings and/or reduce thermal loads. For instance, cities like Medellin or Cali.

It is left for future work to carry out a prototype, which allows corroborating the data obtained from simulations in the design stage of the EAHE. Likewise, it is recommended to carry out prolonged tests of thermal saturation of the ground.

Author Contributions: Conceptualization, S.A.P. and J.E.J.I.; methodology, S.A.P.; software, S.A.P.; validation, S.A.P.; formal analysis, S.A.P.; investigation, S.A.P.; resources, J.E.J.I.; data curation, S.A.P.; writing—original draft preparation, S.A.P.; writing—review and editing, J.E.J.I.

All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ministry of Science, Technology, and Innovation (Ministerio de Ciencia, Tecnología e Innovación)—MINCIENCIAS (Project Contract No. 80740-798-2019).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors wish to thank the Vice-Rectorate for Research and Extension (Vicerrectoría de Investigación y Extensión) from the Universidad Industrial de Santander (Project 8600), and the Energy Mining Planning Unit (Unidad de Planeación Minero Energética—UPME).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. VWC Measurements from each sensor once calibrated.

| Sample %VWC | Sensor 1 | Sensor 2 | Sensor 3 | Sensor 4 | Sensor 5 | Sensor 6 | Sensor 7 |
|-------------|----------|----------|----------|----------|----------|----------|----------|
| 1.0         | 1.1      | 1.2      | 1.0      | 1.4      | 0.9      | 1.5      | 1.4      |
| 2.0         | 2.3      | 1.9      | 1.7      | 2.3      | 2.1      | 2.2      | 2.3      |
| 3.0         | 3.1      | 2.9      | 3.1      | 2.9      | 3.2      | 3.1      | 3.0      |
| 4.0         | 3.9      | 4.2      | 4.2      | 4.3      | 4.1      | 3.8      | 3.9      |
| 5.0         | 4.9      | 4.8      | 5.1      | 5.3      | 5.2      | 5.0      | 4.9      |
### Table A1. Cont.

| Sample %VWC | Sensor 1 | Sensor 2 | Sensor 3 | Sensor 4 | Sensor 5 | Sensor 6 | Sensor 7 |
|-------------|----------|----------|----------|----------|----------|----------|----------|
| 6.0         | 6.2      | 5.9      | 5.8      | 5.9      | 5.9      | 6.2      | 6.1      |
| 7.0         | 6.9      | 7.2      | 7.3      | 6.9      | 6.9      | 6.9      | 7.0      |
| 8.0         | 7.8      | 7.9      | 8.0      | 8.1      | 8.3      | 7.8      | 8.1      |
| 9.0         | 9.1      | 9.3      | 8.8      | 8.9      | 8.9      | 9.0      | 8.7      |
| 10.0        | 10.3     | 10.1     | 9.8      | 10.2     | 10.3     | 10.1     | 10.0     |
| 11.0        | 11.0     | 10.8     | 10.9     | 11.3     | 10.9     | 10.8     | 11.1     |
| 12.0        | 12.2     | 12.1     | 12.2     | 11.9     | 12.4     | 11.8     | 11.9     |
| 13.0        | 13.0     | 13.2     | 13.3     | 12.8     | 13.1     | 13.3     | 12.9     |
| 14.0        | 14.2     | 13.9     | 14.1     | 14.3     | 14.4     | 14.3     | 14.1     |
| 15.0        | 15.4     | 15.2     | 15.0     | 15.3     | 15.2     | 15.3     | 14.9     |
| 16.0        | 15.9     | 16.5     | 16.3     | 16.2     | 15.8     | 15.9     | 15.0     |
| 17.0        | 16.7     | 16.3     | 16.2     | 17.3     | 17.1     | 17.4     | 16.9     |
| 18.0        | 18.5     | 18.6     | 18.3     | 18.0     | 18.2     | 18.1     | 17.8     |
| 19.0        | 18.9     | 19.0     | 19.2     | 19.1     | 18.9     | 19.4     | 19.2     |
| 20.0        | 20.1     | 20.4     | 20.2     | 20.1     | 19.8     | 19.3     | 20.2     |
| 21.0        | 21.0     | 21.2     | 21.5     | 21.2     | 21.4     | 20.8     | 20.8     |
| 22.0        | 22.1     | 21.8     | 21.7     | 22.3     | 22.0     | 22.5     | 22.2     |
| 23.0        | 23.0     | 22.9     | 23.1     | 22.9     | 23.4     | 22.9     | 22.7     |
| 24.0        | 23.7     | 23.9     | 24.0     | 24.0     | 23.6     | 23.8     | 24.1     |
| 25.0        | 25.1     | 25.0     | 25.5     | 25.1     | 25.1     | 25.4     | 24.9     |
| 26.0        | 26.1     | 25.9     | 26.1     | 26.1     | 25.8     | 26.2     | 26.5     |
| 27.0        | 26.9     | 26.9     | 27.2     | 27.1     | 27.4     | 26.8     | 27.3     |
| 28.0        | 28.1     | 27.9     | 28.5     | 27.9     | 28.3     | 28.4     | 28.1     |
| 29.0        | 29.2     | 28.7     | 28.6     | 29.0     | 28.8     | 29.3     | 28.7     |
| 30.0        | 29.9     | 30.2     | 30.4     | 30.2     | 29.7     | 29.8     | 29.7     |

### Appendix B

#### Table A2. Building construction materials and envelope characteristics.

| Construction Elements | Description |
|-----------------------|-------------|
| **Floors**            | Buffer plates: 3000 PSI concrete, rough finish and thickness 7 cm.  
Leveling mortar: Thickness 5 cm, concrete 2500 PSI with \( \frac{3}{4} \)-inch aggregate, mesh 4 mm electro welded, crosslinked of 20 × 20 cm.  
Polished concrete: 3 cm thick, with application surface of hardener with dosage of heavy traffic of 5 kg/m².  
Dilations of 1.5 cm, 2 × 2 m.  
Polished finish. |
| **Masonry**           | Partition walls: Bricks type H15.  
Mortar: 1:3 cement: sand, 1 cm thick, alternating joints between courses. |
| **Sun shades**        | 3.075 × 0.55 × 0.1-m concrete supported on tie beams and masonry H12 of 90 cm. |
| **Ceiling**           | 24 × 24-inch natural fiber panels with thicknesses between 4 and 16 millimeters, attached to 5/16-inch die-cut frame. |
| **Friezes, stuccoes and paintings** | 1.5 cm thick frieze, 1: 3 ratio cement: sand, # 6 sieve.  
Stucco: A mixture of plaster, lime and cement.  
Sanded twice.  
Painting: Two coats of armor-type paint applied with rollers. |
| **Windows and doors** | Windows in colorless natural glass of 5 mm thickness, a single sheet.  
Gasket in the frame.  
Main doors made of glass colorless tempered 10 mm and veneer aluminum. |
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