Contribution of Low Enthalpy Geothermal Energy in the Retrofit of a Single-Family House: A Comparison between Two Technologies

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Abstract: In recent years, the European Union has developed a sustainable, competitive, safe, and "decarbonised" energy approach. To achieve this objective, especially in highly urbanized contexts, there is a need to drastically improve the energy behavior of buildings and related energy systems. For this purpose, the aim of this paper is to analyse two very promising technologies that exploit the geothermal energy of the ground: the Earth-to-Air Heat eXchanger (EAHX) and the Ground Source Heat Pump (GSHP). These two systems are used as an energy retrofit strategy for the air conditioning system in an existing single-family house, located in Naples (south Italy). The building and the related systems are dynamically simulated using the DesignBuilder software. The results show energy savings of these two systems (compared to a traditional solution with an air-to-water heat pump) between 13% and 28%, with a total yearly primary energy consumption of about 80 kWh/m^2 for the case with EAHX and around 67 kWh/m^2 for the case with GSHP.

Keywords: Earth-to-Air Heat eXchanger; Ground Source Heat Pump; Low enthalpy geothermal energy; HVAC; Energy retrofit; Dynamic simulation.

1. INTRODUCTION

In recent years, effective solutions have been sought all over the world to solve the problems of environmental pollution, global warming, and energy shortages. In Europe, buildings are responsible for about 40% of energy consumption and 36% of CO_2 emissions [1,2]. The European Union is committed to developing a sustainable, competitive, safe, and "decarbonised" energy approach. In order to achieve this objective, in the "2030 Climate and Energy Framework" report [3] significant targets are set for the reduction of energy consumption, the increase in the use of renewable energy sources, and the reduction of polluting emissions by 2030. Among the several strategies, the most effective one seems to be to promote renewable energy sources in the building sector [4].

Among the renewable energy sources, geothermal energy is a form of energy linked to the endogenous heat of the earth. After solar energy, the heat that comes from the earth is the most important renewable energy source. The temperature of the ground is usually higher in winter and lower in summer than the outside air. Moreover, after a few meters of depth, it reaches an almost constant value throughout the year [5,6]. For these reasons, this type of renewable resource is a valid alternative to traditional air conditioning systems that exploit the external air and that are usually installed in buildings. The geothermal systems can be classified in low, medium, or high enthalpy, based on the temperature of the source. In this paper, the first type of geothermal system is considered.

Low-temperature geothermal energy (often called "low enthalpy" geothermal energy) is a renewable thermal energy resource that uses heat at a temperature below 90°C as an energy source. Geothermal plants exploit the thermal energy naturally available in the subsoil (within 200 m from the ground level). In the international literature [7], this type of geothermal resource is referred to as Near Surface Geothermal Energy (NSGE) or Shallow Geothermal Energy (SGE), although the terms Low Temperature and Low Enthalpy are also widespread.

Medium and high-temperature geothermal resources are found only in geologically active areas such as volcanic or thermal ones whereas low-temperature geothermal resources can be exploited in completely "normal" geological conditions, so it is available everywhere [8].

Two typical systems that exploit low enthalpy geothermal energy are:

1. Geothermal heat pump (also called Ground Source Heat Pump, GSHP);
2. Geothermal heat exchangers, such as the Earth-to-Air Heat eXchanger (EAHX).

The geothermal heat pump, by means of vertical or horizontal undergrounded probes, uses an almost constant temperature source/tank throughout the year regardless of seasonal climatic fluctuations. For this reason, GSHPs are more efficient than both traditional air-to-water heat pumps and other technologies used for air conditioning [9]. In fact, if compared with conventional heat generators, the geothermal heat

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pumps offer a reduction in energy consumption of 30-70% in heating mode and 20-50% in cooling mode [10]. In many cases, the geothermal heat pump is coupled to a solar thermal storage system: solar assisted ground source heat pump (SAGSHP) systems have recently been examined by many researchers. Numerous review articles have been written on solar assisted heat pump (SAHP) systems, studying different types of coupled solar and heat pump systems. The literature review showed that solar thermal energy affects the efficiency of GSHPs. The application of these hybrid systems leads to significant energy savings by using free heat resources stored in the ground and the sun. With these systems, there is a further advantage that solar energy increases the temperature of the liquid entering the evaporator of the heat pump thus causing an increase in the energy efficiency of the heat pump. Solar energy has the additional advantage of recharge-ing the ground source to achieve a stable ground temperature and a high coefficient of performance of the heat pump [11,12]. In many other cases, however, the geothermal heat pump is combined with a photovoltaic solar system, where the resulting electricity is partly used to operate the heat pump in order to meet the heating and cooling needs of the building and partly used for other electrical loads [13,14]. Many scientific articles analyse energy conversion systems based on photovoltaic and GSHP systems that serve single-family and multi-family buildings and whose primary energy consumption falls in the range of values between 57 kWh/m^2 and 67 kWh/m^2 [15-17].

The earth-to-air heat exchanger (EAHX) consists of one or more pipes, laid in the ground, used to cool (in summer) or preheat (in winter) the air to be supplied to a building. The performance of the earth-to-air heat exchangers depends on several factors: shape and diameter of the pipes; fluid velocity; depth of pipe laying; the number of tubes; the intensity of solar radiation; soil properties.

The diameter of the pipes should be between 0.2 and 0.3 m and the speed of the fluid (in this case air) should be between 1 m/s and 3 m/s, which seem to individuate the right compromise between heat exchange and pressure drops. The typical length of underground pipes is between 30 and 100 m. They are generally laid at a depth between 2 and 4 m below the ground level [18-20].

Earth-to-air heat exchangers can be divided into two types; open loop or closed loop.

In the open-loop systems, there is a continuous supply of external air that is sucked into the exchanger, inside which it is treated by the heat exchange with the ground. This allows ventilation in the rooms and a certain cooling in summer.

Instead, in closed-loop systems, the same air (or fluid in general) always recirculates cyclically in the exchanger from the building to the EAHX and vice versa.

As in the case of GSHP, the EAHX can be designed with vertical or horizontal pipes. The number and length of pipes to be used depends on numerous factors such as the required airflow rate to be guaranteed in the building and the space available for their installation [20]. After analysing the scientific literature, it is clear that this technology is very promising; in fact, numerous researches have been carried out to develop analytical and numerical models for the analysis of these systems [21,22]. Many researchers have developed equations and procedures too complex to be reworked into design equations, so it is necessary to proceed by trial and error. Bisoniya [23] developed a one-dimensional model of EAHX systems using a series of simplified design equations. The developed equations allow designers to calculate the heat transfer, the convective heat transfer coefficient, pressure losses, and the length of the pipe of the earth system. All-over the world, researchers have studied the performance of the earth-to-air heat exchangers through numerical models or calculation methods, in a large number of distinct scenarios: the results obtained are well summarized in the review article [24] in which they are classified by comparing the main systems based on EAHX up to 2018.

Among the several applications in the air conditioning system, in [25] the use of an ASHP (Air-Source Heat Pump) coupled to an earth-to-air heat exchanger (EAHX) is evaluated to reduce energy consumption in buildings. Most of the works combine EAHX with mechanical ventilation for the redevelopment of existing buildings [26,27]. Others instead propose a hybrid version of this system, placing the exchanger upstream of the air handling unit in place of the classic air-to-air heat exchanger [28-30]. In all these studies, the savings obtained using this system are around 30% for yearly primary energy consumption, and this solution is particularly suitable for cold climates.

The aim of this paper is to analyse these two very promising technologies that exploit the geothermal energy of the ground: the Earth-to-Air Heat eXchanger (EAHX) and the Ground Source Heat Pump (GSHP). These two systems are used as an energy retrofit strategy for the air conditioning system in an existing single-family house, located in Naples (south Italy). The building and the related systems are dynamically simulated using the DesignBuilder software. The total yearly primary energy consumption and the energy savings compared to a traditional solution with an air-to-water heat pump are evaluated. Although the current literary scientific panorama highlights the positive contribution that low enthalpy geothermal energy can have in the energy saving of buildings, at the best of the authors' knowledge there is no energy comparison between the two above-mentioned systems. So, the main innovative aspect of this paper is the use of the geothermal heat pump and the EAHX for the energy retrofit of an existing building in the Mediterranean climate and mainly the energy comparison between these two systems.

METHODOLOGY

The existing building is located in Naples and after several inspections, it has been modeled through the use of DesignBuilder [31]. DesignBuilder is a software, based on the EnergyPlus calculation engine, to dynamically simulate the energy needs of buildings and related systems. The U.S. Department of Energy has made numerous tests available to validate the models and components used by the software [32,33]. The climatic data used by the software are taken from [34].

The main equation used for conduction is based on the algorithm Conduction Transfer Function (CTF), while for outside and inside convection, the algorithms DOE-2 [35] and TARP [36] are used, respectively.

DesignBuilder uses an equation-fit based model [37,38] to simulate the energy performance of heat pumps. Equations (1)–(4) characterize the load curves of the heat pumps:

$$\frac{Qc}{Q_{c,ref}} = A_1 + A_2 \frac{T_L}{T_{ref}} + A_3 \frac{T_S}{T_{ref}} + A_4 \frac{\dot{V}_L}{\dot{V}_{Lref}} + A_5 \frac{\dot{V}_S}{\dot{V}_{Sref}} \ , \tag{1}$$

$$\frac{Power,c}{Power_{c,ref}} = B_1 + B_2 \frac{T_L}{T_{ref}} + B_3 \frac{T_S}{T_{ref}} + B_4 \frac{\dot{V}_L}{\dot{V}_{Lref}} + B_5 \frac{\dot{V}_S}{\dot{V}_{Sref}} \ , \tag{2}$$

$$\frac{Qh}{Q_{h,ref}} = C_1 + C_2 \frac{T_L}{T_{ref}} + C_3 \frac{T_S}{T_{ref}} + C_4 \frac{\dot{V}_L}{\dot{V}_{Lref}} + C_5 \frac{\dot{V}_S}{\dot{V}_{Sref}} \ , \tag{3}$$

$$\frac{Power,h}{Power_{h,ref}} = D_1 + D_2 \frac{T_L}{T_{ref}} + D_3 \frac{T_S}{T_{ref}} + D_4 \frac{\dot{V}_L}{\dot{V}_{Lref}} + D_5 \frac{\dot{V}_S}{\dot{V}_{Sref}} \ , \tag{4}$$

where:

- A_1–D_5: Equation fit coefficients for the cooling and heating mode;
- T_{ref}: Reference temperature, K;
- T_L: Load side entering water temperature, K;
- T_S: Source side entering water temperature, K;
- $\dot{V}_L$: Load side volumetric flow rate, m^3/s;
- $\dot{V}_S$: Source side volumetric flow rate, m^3/s;
- $V_{L,ref}$: Reference load side volumetric flow rate, m^3/s;
- $V_{S,ref}$: Reference source side volumetric flow rate, m^3/s;
- Qc Load side heat transfer rate (cooling mode), W;
- $Q_{c,ref}$: Reference load side heat transfer rate (cooling mode), W;
- $Power_c$: Power needed (cooling mode), W;
- $Power_{c,ref}$: Reference power needed (cooling mode), W;
- Q_h: Load side heat transfer rate (heating mode), W;
- $Q_{h,ref}$: Reference load side heat transfer rate (heating mode), W;
- $Power_h$: Power needed (heating mode), W;
- $Power_{h,ref}$: Reference power needed (heating mode), W.

Based on the construction data of the selected heat pump, the coefficients A1–D5 are entered in the model to simulate the energy performances. They refer to the performance at partial loads of heat pumps present in the DesignBuilder database.

Once the thermal and technologic characteristics of the building envelope and the HVAC systems are set into DesignBuilder, the model has been validated using the available energy bills. In this regard, a minimum acceptable error has been set (ε=5%). Having only two calibration parameters (electricity consumption and natural gas demand for heating), a simple method of calibration was used to evaluate the current error ε_{uv}, with the following equation [39]:

$$\varepsilon_{uv} = \sqrt{}[(V_{real} — V_{simulate})^2/(V_{real})^2], \tag{5}$$

where:

- V_{real} is the value obtained from available data.

- $V_{simulate}$ is the value obtained from simulation.

The level of convergence reached can be defined as more than satisfactory if $\varepsilon_{uv} \leq 5\%$.

Regarding the proposed geothermal systems, once the model has been validated it has been necessary to define the temperature of the ground in DesignBuilder.

The temperature of the ground is obtained from the Kusuda relation [40,20]:

$$T_g(D,t) = T_{av} - A \cdot \exp\left[-D \cdot \sqrt{\frac{\pi}{365\cdot\alpha_g}}\right] \cdot \cos\left[\frac{2\pi}{365} \cdot \left(t - t_{T_{min}} - \frac{D}{2} \cdot \sqrt{\frac{365}{\pi\cdot\alpha_g}}\right)\right], \tag{6}$$

where:

- *Tg (D,t): ground temperature at a depth D after t days (starting from 1 January), °C;*
- *Tav: yearly average temperature of the outdoor environment on the basis of statistical information, °C;*
- *A: amplitude of the temperature annual oscillation, °C;*
- *t: sequential number of the day (1 refers to 1 January);*
- *tTmin: sequential number of the day corresponding to the minimum ground temperature, according to statistical data (1 refers to 1 January);*
- *D: depth of the ground, m;*
- *α_g: daily equivalent thermal diffusion of the ground [m2/day].*

The total length of the geothermal probes has been calculated with a simplified relation that considers the specific heat extraction of probe (W/m) and the evaporator capacity (W). A typical soil with solid rock and several hours of system operation of 2400h have been considered, which in Table 1 corresponds to a specific heat extraction value of 50 W/m (m of probe – value recommended in [41]).

Table 1. Specific Heat Extraction Value in W on Probe Meters

Hours of system operation	2400 h
Soil	Specific heat extraction in W/m of probe
A typical soil with solid rock and water-saturated sediments	50

The evaporator capacity depends on the COP/EER and the heating/cooling load, as follows:

- winter conditions

$$P_{EV} = \frac{COP-1}{COP}\, x\, Q_h \tag{7}$$

where:

- P_{EV} is the capacity of the evaporator of the heat pump in heating mode, W;
- COP is the Coefficient Of Performance of the heat pump in heating mode;
- Qh is the heating load, W.

- summer conditions

$$P_{CO} = \frac{EER+1}{EER}\, x\, Q_c \tag{8}$$

where:

- P_{CO} is the capacity of the condenser of the heat pump in cooling mode, W;
- EER is the Energy Efficiency Ratio of the heat pump in cooling mode;
- Qc is the cooling load, W.

Once the specific heat extraction and the capacity of the evaporator (in heating mode) and condenser (in cooling mode) are known, the total length of geothermal probes can finally be calculated from the following relation:

$$L_P = \max\left(\frac{P_{EV}}{q}; \frac{P_{CO}}{q}\right) \tag{9}$$

where:

- Lp is the total length of the geothermal probes, m;
- q is the value of specific heat extraction, W/m.

CASE STUDY

The building is a single-family house located in Naples in southern Italy. In Figure 1, an aerial photogrammetry of the existing building is shown. Naples is a city characterized by mild winters and hot summers. The building stands on one level with a height of 4.5 m, for a total area of approximately 85 m^2.

The building envelope is made up of yellow Neapolitan tuff masonry of 35 cm and 60 cm (Nord) and a layer of cork insulation for the vertical walls along with hemp fiber for the sloping roof. Table 2 indicates the unitary thermal transmittances of the existing envelope components, all ones minor than the limit values based on the current Italian rule [42].

Figure 1: Aerial photogrammetry of the existing building.

Table 2: Unitary Thermal Transmittances of the Building Envelope Components

Component	Transmittance [W/m^{2}K]		Limit Transmittance Zone C [W/m^{2}K] [42]
Floor	0.21	<	0.38
Roof	0.27	<	0.33
Wall 51 cm	0.22	<	0.34
Wall 70 cm	0.27	<	0.34
Window	1.71	<	2.2
Entrance door	0.7	<	2.2

The HVAC system presents an invertible air-to-water heat pump for heating and cooling and a mechanical ventilation system. Radiant floors are installed as terminals for heating and cooling systems in each room of the apartment. The Domestic Hot Water (DHW) production is entrusted to a dedicated air-to-water heat pump.

In addition to the building, the lot also consists of a garden that lends itself to the installation of geothermal probes for the GSHP or the ground-air exchanger.

In Table 3, the nominal capacity, the coefficient of performance (COP), and the energy efficiency ratio (EER) of the invertible air-to-water heat pump are shown.

The total external airflow rate of the mechanical ventilation is 461 m^3/h system based on UNI 10339: 2005 [43]. According to classification reported in DPR 412/93 [44], Naples belongs to climatic zone C with 1034 Heating Degree Days; for this zone, it is mandatory that the heating system can only be turned on from 15th of November to 31st of March for a maximum of 10 hours per day. There are no time limits imposed by law regarding the cooling system.

Table 3: Thermal Parameters of the Existing Air-to-Water Heat Pump

Air-to-Water Heat Pump	Nominal Capacity [kW]	COP/EER [-]
Heating	7.0	4.6
Cooling	12.2	4.7
DHW	1.9	3.7

For these reasons, the chosen schedules of the HVAC systems are:

- Heating system: from 15th of November to 31st of March from 6:00 to 10:00 and from 16:00 to 22:00;
- Cooling system: from 1st of June to 30th of September from 9:00 to 11:00 and from 15:00 to 20:00;
- Mechanical Ventilation/EAHX: same schedules of heating and cooling systems.

To evaluate the best strategy using the low enthalpy geothermal energy in order to improve the energy performance of the existing building, three scenarios have been hypothesized:

Case 1: an air-to-water heat pump and radiant panels for heating and cooling, with a mechanical ventilation system;

Case 2: case 1 + the earth-to-air heat exchanger (open loop) added to the mechanical ventilation system;

Case 3: a ground source heat pump and radiant panels for heating and cooling, with a mechanical ventilation system.

In all the examined cases, a dedicated air-to-water heat pump is considered for the DHW production.

In Table 4 and **5**, the main characteristics of the designed EAHX, GSHP, and air-to-water heat pump for the DHW are shown.

For the three scenarios, a winter indoor set point of 20°C and a summer indoor set point of 26°C were set.

Table 4: Main Characteristics of HEAX and GSHP Systems

EAHX		**GSHP**	
Soil			
Thermal capacity		2 MJ/m^3·K	
Thermal conductivity		1.5 W/m·K	
Undisturbed temperature		17 °C	
Characteristics of the EAHX pipes		**Characteristics of the GHSP probes**	
Type	horizontal pipes	Type	vertical probes
Tube material	PP	Probes material	PE-Xa
Thermal conductivity	0.28 W/m·K	Thermal conductivity	0.40 W/m·K
Depth	3 m	Depth of installation of the collectors	1.5 m
Length	80 m	Length	60 m
Diameter	0.2 m	Shape	single U
Tube slope	2.50%	Number of probes	2

Table 5: Thermal Parameters of the Proposed Heat Pumps

Ground Source Heat Pump	**Nominal Capacity [kW]**	**COP/EER [-]**
Heating	7.5	4.6
Cooling	12.5	8.2
Air-to-water heat pump for DHW	1.9	3.7

RESULTS

The first results concern the reduction of primary energy consumption when the HVAC system exploits the geothermal energy of the ground. As can be seen in Figure 2, the influence of the EAHX on the primary energy is more noticeable for cooling requirements (Figure 2 a and b). In fact, by inserting the EAHX, there is a reduction of the primary energy for cooling from 13.5 kWh/m^2 to 3.7 kWh/m^2 (i.e., -73%, a relevant value).

However, the influence that this system has on heating consumption is less significant (only 4%). However, this value is certainly due to the climatic characteristics of the installation site. In fact, Naples is characterized by mild winters, in which the air temperature hardly reaches very low values.

Different results occur when the GSHP is considered. As can be seen from Figure 2 (c), the heating primary energy consumption decreases from 23.7 kWh/m^2 to 9.5 kWh/m^2 (-60 %) compared to the air-to-water heat pump, while the cooling primary energy consumption decreases from 13.5 kWh/m^2 to 2 kWh/m^2 (-85 %).

The influence on the total yearly primary energy consumption of the GSHP and EAHX compared to the existing HVAC system is highlighted in Figure 3. Both technologies bring to a relevant reduction in energy consumption (13-28 %). Obviously, with reference to the mild climate of Naples, the geothermal heat pump seems to be more efficient due to the not extreme winter conditions and to the already low energy consumption for heating. This last result is consolidated if we look at the reduction of CO_2 emissions shown in Figure 4. In fact, with reference to case 1, the yearly CO_2 emissions are 25.7 kg/m^2, which become 22.5 kg/m^2 (-12 %) for the case 2 and 18.7 kg/m^2 (-27 %) for the case 3.

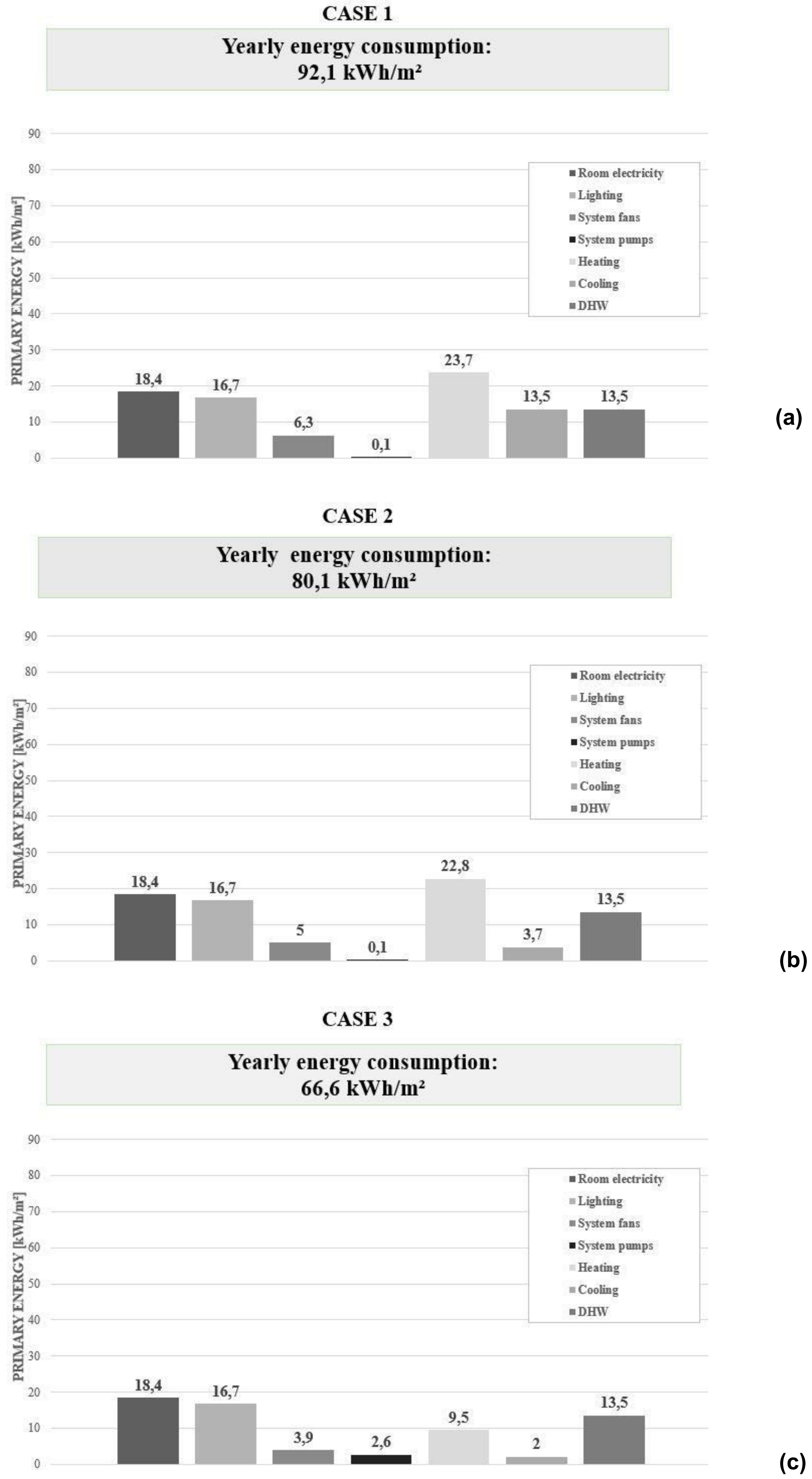

Figure 2: Yearly primary energy consumptions a) case 1 (air-to-water heat pump + MV); b) case 2 (air-to-water heat pump + EAHX); case 3 (geothermal heat pump + MV).

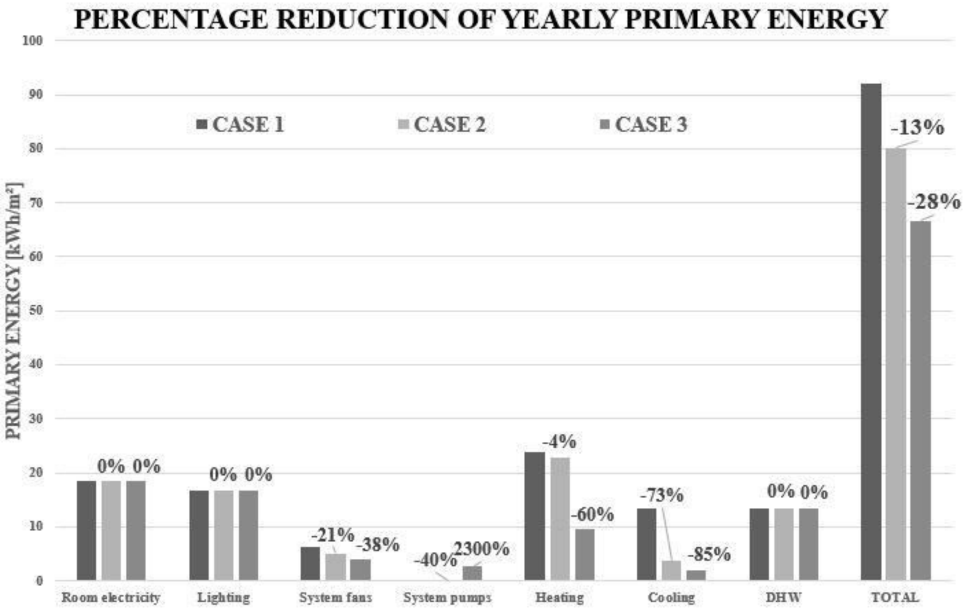

Figure 3: Yearly primary energy consumption for the three cases and percentage reduction compared to case 1.

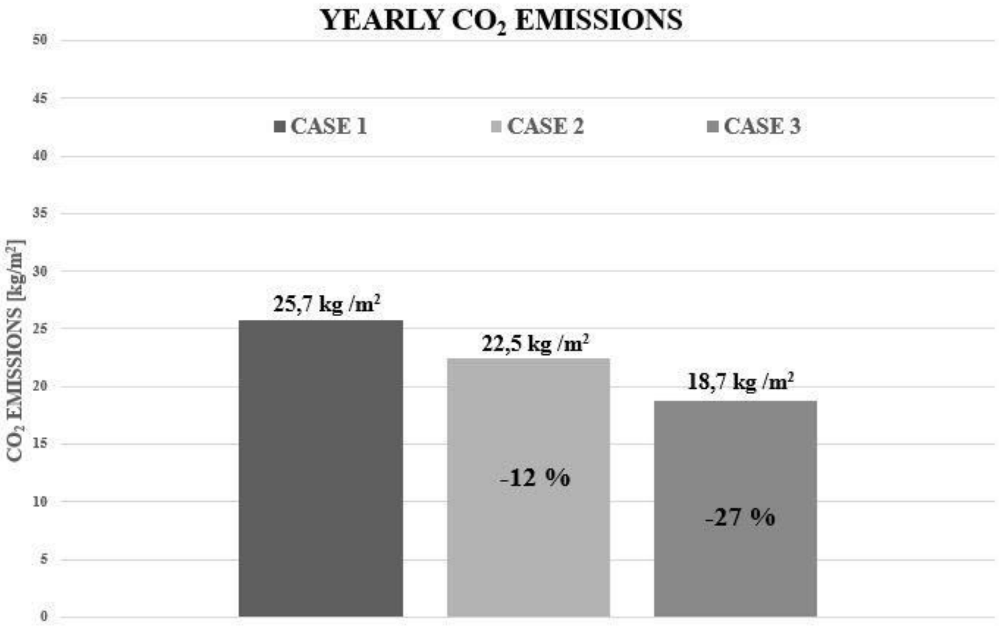

Figure 4: Yearly CO_2 emissions for the three cases and percentage reduction compared to case 1.

CONCLUSIONS

This paper investigates the contribution of two systems that exploit the low enthalpy energy of the ground in the energy retrofit of an existing building located in southern Italy.

The two systems are: an earth-to-air heat exchanger (characterized by horizontal buried pipes) that uses the heat transfer with the ground to pre-heat or pre-cool the external air to be introduced into the building; the other system is a ground source heat pump which, by means of vertical underground probes, exploits the ground as a thermal energy tank and acts as a heat generator alternative to the traditional air-to-water heat pump.

The building and the related systems are dynamically simulated using the DesignBuilder software.

The results show that the two systems that exploit the renewable energy of the ground represent a valid energy retrofit strategy, reaching a relevant reduction of primary energy: 92.1 kWh/m^2 for the case with existing HVAC solution (based on a traditional air-to-water heat pump), 80 kWh/m^2 in the case of EAHX (-13 %) and about 67 kWh/m^2 (-28 %) when we considered the GSHP as a generator.

Similar results occur when considering the reduction of CO_2 emissions. In fact, the use of GSHP allows a reduction of CO_2 emissions of about -27% (-12% when the EAHX is considered).

In conclusion, by comparing these two systems, the GSHP seems more suitable for the retrofit strategy. This can partly be explained considering that the location where the building is placed has a typical Mediterranean climate, where winters are usually mild; therefore in the case of the EAHX, the heat exchange with the ground is not very efficient.

Future developments of the article will be aimed at evaluating whether a technical-economic analysis comparing the two systems will confirm the energy results presented in this paper.

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