The Use of Ground Source Heat Pump to Achieve a Net Zero Energy Building

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Abstract: Currently, ground source heat pump (GSHP) technology is being studied, as the use of the ground as a source of renewable energy allows significant energy savings to be obtained. Therefore, it is useful to quantify how these savings help to achieve the energy balance of a Net Zero Energy Building (NZEB) compared to an air source heat pump or a condensing boiler coupled to a chiller. This paper assesses how these savings affect the number of photovoltaic panels installed on the roof of a building to obtain the NZEB target. The study is conducted by dynamic simulation for a building used as a bed and breakfast, virtually placed in two Italian towns. The energy savings and reduction of CO₂ emissions, the percentage of renewable energy used, and the photovoltaic surface needed are assessed. Finally, the discounted payback period is calculated. The results show that the GSHP, unlike the systems to which it is compared, allows an NZEB to be obtained by balancing yearly energy consumption with energy production systems which only use on-site renewable energy sources (by exploiting the surface available on the roof) for both of the climatic conditions considered. GSHP also allows primary energy requests equal to or less than 57 kWh/m² to be obtained.

Keywords: ground source heat pump; NZEB; dynamic simulation; HVAC system; renewable energy sources; photovoltaic panels

1. Introduction

In Europe, buildings are responsible for about 36% of total CO₂ emissions. Thus, European Directives have been issued to reduce these emissions by improving energy performance of buildings, i.e., the Energy Performance Building Directive, so-called “EPBD” [1] and “EPBD recast” [2]; successively, the European Directive 2018/844 [3] aims to completely decarbonise the building stock by 2050.

This can be achieved by transforming current buildings into nearly Zero Energy Buildings (nZEBs) and employing mainly renewable energy sources [4]. However, the goal of Net Zero Energy Buildings (NZEBs) is still far from being achieved.

An NZEB is a building characterized by opaque and transparent components with optimal values of thermal parameters (for example, a low unitary thermal transmittance), in which the position of the openings helps natural ventilation and the most energy efficient systems are installed; for these reasons, this building has a very low energy requirement, completely satisfied by renewable energy sources [1,5,6]. In practice, to obtain this target, many parameters must be fixed, such as the control volume for applying the energy balance, and the time base of this balance, i.e., monthly, seasonal, or annual [7]. Berggren and Wall [8] analyse the importance of normalizing the balance referring to both internal and external boundary conditions and highlighting the importance to keep the indoor
temperature under control. Moreover, it is important to understand if solely on-site renewable energy sources are sufficient; in fact, D’Agostino et al. [9] highlight how in densely urbanized cities the roof of a building is the main useful space if the use of on-site renewable sources is desired. In this case, therefore, the satisfaction of the energy balance is greatly influenced by the surface-to-volume ratio of the building. Other factors concern the type of renewable energy source to be used. Among renewable energy systems, those that use solar energy are common, such as photovoltaic systems, solar thermal systems, and photovoltaic/solar collectors. Many different parameters relating to solar energy have been investigated, such as the choice of the type of system [10,11] and the drop in performance of different systems due to cell degradation [12,13]. To enhance the use of renewable energy sources for obtaining a ZEB, Bae et al. [14] identify an innovative solution based on a trigeneration system consisting of a geothermal heat pump and solar thermal-photovoltaic system. Furthermore, Ferrante et al. [15] and D’Agostino et al. [16] underline the importance of using passive solutions, integrated design and other systems, such as improvement of the thermal characteristics of the building envelope or using solar and wind energy micro-generation.

Despite the widespread use of renewable energy sources and innovative systems, achieving an energy balance equal to zero (i.e., yearly energy consumption equal to yearly energy production from renewables) is not easy and this is not sufficient to characterize an NZEB; it can often cause additional stress on the existing energy infrastructure when the plant powered by renewable energy sources is oversized to satisfy the balance and exchanges with the grid. [17]. Franco and Fantozzi [18] analyse the operating performance of a small-size photovoltaic system and its possible utilization for promotion of self-consumption policies of nZEBs, reaching the conclusion that in this type of building the interaction with the national electricity grid remains high. Similar results were found by Rey-Hernández et al. [19] who found that the primary energy consumption and energy production from renewable sources of an existing LEED-certified (Leadership in Energy and Environmental Design) nZEB in Spain were higher than the standards recommended in the EPBD [1], due mainly to the national energy conversion factors. Thus, it is important to consider a budget to implement and improve control strategies.

Given this, to achieve the NZEB target, it is first essential to reduce the energy needs of the building. In Ascione et al. [20], the boundary conditions are analysed, as well as the design criteria and fundamental concepts for an NZEB; it is highlighted that a good design leads to drastically reduced energy needs for heating and cooling. In Buonomano et al. [21], for a non-residential NZEB in Mediterranean climates the obtained energy demand is 3.9 kWh/m²y for heating and 6.7 kWh/m²y for cooling. Feng et al. [22] highlight how, for the New Building Institute of the U.S., the target NZEB is obtained when the ratio between renewable energy production intensity and energy use intensity is equal to 1 and the building has a primary energy consumption equal to or less than 57 kWh/m².

The ground source heat pump (GSHP) is one of the various high efficiency systems that are suitable for reducing energy consumption. The GSHP usually has a higher coefficient of performance (COP) than the more common air source heat pump, due to the more favourable and stable thermal level of the soil compared to the outside air [23]. In fact, particularly for the great depths at which geothermal heat pumps with vertical probes work, the soil temperature is higher in winter and lower in summer than that of the outside air. This improves the ideal COP of the GSHP and therefore also the achieved COP (see also Equations (6) and (7)). Although it is a system that exploits the soil and may have considerable surface requirements, there are innovative systems that exploit the foundations of buildings for the implementation of geothermal probes. Despite the difficulty often encountered in finding an available surface on which to lay the probes on site, Kotarela et al. [24] highlight that the combined use of a photovoltaic system and geothermal heat pump is one means of reducing dependence on fossil fuels while simultaneously avoiding overloading of the electricity grid. Indeed, in Carotenuto et al. [25,26], innovative ground systems are analysed using the finite elements method. In this geothermal configuration, freezing probes are inserted in foundation pylons to exploit the low enthalpy of the ground. It is also important to bear in mind that geothermal heat pumps, both in summer and winter, exploit the renewable energy of the soil. Revesz et al. [27]
investigate the GSHP in urbanized cities where the heat from an underground tunnel (the ground surrounding the infrastructure) could be exploited to improve the heating mode operation of a GSHP. Thus, the advantage of this technology can be used to satisfy the need to use renewable energy sources for civil and non-civil use. In the literature, this system is coupled with several innovative complementary systems. In Buonomano et al. [28], geothermal energy coupled with solar energy is used and investigated in a trigeneration plant. Huang et al. [29] investigate the optimization of a large scale solar-assisted ground source heat pump for district heating, finding an optimal match between the size of the ground heat storage, the collector area, and the tank volume. In [30,31], the coupling between the GSHP and the photovoltaic/thermal system is analysed, demonstrating how the use of these systems together increases the thermal efficiency of the collectors; the electrical efficiency of the cells remains high without the risk of cell damage due to overheating. Due to its characteristics and high efficiency in terms of energy saving, CO₂ emissions reduction, and renewable energy source use, this system can easily be implemented in buildings to achieve more easily the NZEB target. However, little research has been undertaken about this system in the literature.

In Fedajev et al. [32], with reference to an nZEB, the influence of different earth heat exchangers linked to a GSHP and thermal storage is examined, for the very harsh climatic conditions of Finland; the importance of the thermal storage to achieve the goal of an nZEB is shown.

In a review article, Gao et al. [33] highlight the different potentialities of the technologies that can be coupled to the geothermal heat pump, suggesting this technology can be used in zero energy buildings.

In the technical-scientific literature to date, little examination has been made of the contribution of GSHPs to obtain a zero-energy balance in an NZEB and their influence in reducing the photovoltaic surface to be used in densely urbanized cities. Often these systems are analysed separately without any reference to the reduction of photovoltaic panels to be installed. Therefore, this paper analyses the aforementioned contribution by comparing the GSHP to other systems, such as an invertible (“reversible”) air source heat pump or a condensing boiler coupled to a chiller, in order to meet the NZEB target in different climatic conditions and to evaluate the photovoltaic surface needed to achieve the status of an NZEB compared to that available on the roof. To this aim, a case study building used as a bed and breakfast (B&B) and virtually located in two Italian towns with different climatic conditions is analysed. Using the dynamic energy simulation software, DesignBuilder, a detailed energy analysis is carried out. The procedure is partially validated by comparing the building energy requirements with literature data. Moreover, other important results are obtained regarding the primary energy consumption, the reduction of CO₂ emissions, and the percentage of renewable energy used for the various solutions. Finally, a technical-economic analysis using the discounted payback is performed.

2. Methodology

2.1. Model Description

Referring to a case study building, the seasonal energy consumption and CO₂ emissions of the building’s energy systems (in particular, in the case with GSHP) are evaluated.

First, the building to be designed should be characterised by low energy needs. Therefore, optimal thermal characteristics for the building envelope must be chosen to minimize the thermal losses in winter, while the free heat gains should be maximized in winter and minimized in summer. To this end, optimal thermal insulation, compact form, and innovative technologies should be selected [16].

Subsequently, the HVAC (heating, ventilation and air-conditioning) system and other building energy systems must be chosen and designed to minimize the primary energy requirements [22] by using energy-efficient solutions.

Therefore, the use of a GSHP is considered, and it is subsequently determined if this choice makes it easier to reach the NZEB target (i.e., the energy balance equal to zero between energy required by the building-system complex and energy produced from renewable sources).
The building of the case study is virtually located in two different Italian climatic zones and the energy analysis is performed through dynamic building energy performance simulation software, i.e., DesignBuilder [34], based on the EnergyPlus calculation engine. The U.S. Department of Energy has performed several validation tests referring to EnergyPlus [35,36]. The climatic data are taken from ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) [37].

The focus of the paper is an energetic, environmental, and technical-economic comparison between various generators of thermal energy: a GSHP characterized by vertical probes, an air source heat pump, and a condensing boiler plus an air-cooled chiller.

Regarding the DesignBuilder software, the CTFM (Conduction Transfer Function Module) is selected based on the algorithm “conduction transfer function”. Moreover, the algorithm DOE-2 [38] is set for the outside convection and the algorithm TARP [39] for the inside convection [40].

The heat pumps are simulated by DesignBuilder using an equation-fit based model [41,42] to predict the heat pumps’ performance for cooling and heating modes. Equations (1)–(4) characterize the load curves of the heat pumps:

\[
\frac{Q_c}{Q_{c,ref}} = A_1 + A_2 \frac{T_L}{T_{ref}} + A_3 \frac{T_S}{T_{ref}} + A_4 \frac{\dot{V}_L}{V_{L,ref}} + A_5 \frac{\dot{V}_S}{V_{S,ref}},
\]

\[
\frac{\text{Power},c}{\text{Power}_{c,ref}} = B_1 + B_2 \frac{T_L}{T_{ref}} + B_3 \frac{T_S}{T_{ref}} + B_4 \frac{\dot{V}_L}{V_{L,ref}} + B_5 \frac{\dot{V}_S}{V_{S,ref}},
\]

\[
\frac{Q_h}{Q_{h,ref}} = C_1 + C_2 \frac{T_L}{T_{ref}} + C_3 \frac{T_S}{T_{ref}} + C_4 \frac{\dot{V}_L}{V_{L,ref}} + C_5 \frac{\dot{V}_S}{V_{S,ref}},
\]

\[
\frac{\text{Power},h}{\text{Power}_{h,ref}} = D_1 + D_2 \frac{T_L}{T_{ref}} + D_3 \frac{T_S}{T_{ref}} + D_4 \frac{\dot{V}_L}{V_{L,ref}} + D_5 \frac{\dot{V}_S}{V_{S,ref}},
\]

where:

- \(A_1–D_5\): Equation fit coefficients for the cooling and heating mode;
- \(T_{ref}\): Reference temperature;
- \(T_L\): 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;
- \(Q_c\): Load side heat transfer rate (cooling mode), W;
- \(Q_{c,ref}\): Reference load side heat transfer rate (cooling mode), W;
- \(\text{Power},c\): Power needed (cooling mode), W;
- \(\text{Power}_{c,ref}\): 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;
- \(\text{Power},h\): Power needed (heating mode), W;
- \(\text{Power}_{h,ref}\): Reference power needed (heating mode), W.

The coefficients \(A1–D5\) are entered in the heat pump model to simulate the performances. They refer to the performance at partial loads of heat pumps present in the DesignBuilder database. After inputting the dimensions of the HVAC system and choosing the heat pump of the required size, the software chooses suitable values of these coefficients basing on information from the manufacturer.
A library of templates containing pre-defined manufacturers’ heat pump data is provided to allow an early stage analysis to be carried out.

In addition, the undisturbed temperature of the ground is needed in order to evaluate the seasonal efficiency of a GSHP. To this end, the equation of Kusuda [43] is applied:

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

where:

- $T_g(D, t)$: ground temperature at a depth $D$ after $t$ days (starting from 1 January), °C;
- $T_{av}$: 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);
- $t_{T_{min}}$: 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;
- $\alpha_g$: daily equivalent thermal diffusion of the ground (m$^2$/day).

For these parameters, the values reported in Table 1 are used.

### Table 1. Ground temperature and other parameters which affect the energy performance of the ground source heat pump (GSHP).

| Parameter                  | Milan   | Palermo |
|----------------------------|---------|---------|
| $T_g$ °C                   | 13 °C   | 19 °C   |
| $T_{av}$ °C                | 12.5 °C | 18.6 °C |
| $A$ °C                     | 9.4 °C  | 5 °C    |
| $t$ (21 December)          | 335     | 335     |
| $t_{T_{min}}$ (15 January) | 15      | 33      |
| $D$ m                      | 80      | 80      |
| $N$° of probes             | 4       | 4       |
| Type of probe              | U-bend tube | U-bend tube |
| $\alpha_g$ m$^2$/day       | 0.0821  | 0.0821  |

(*) From ASHRAE [37].

The seasonal energy performance of the heat pumps and chiller (seasonal coefficient of performance (SCOP) for heating operation, seasonal energy efficiency ratio (SEER) for cooling) are calculated by means of Equations (6) and (7):

$$SCOP = \frac{\eta_{II} (\Theta_h + 273.2)}{(\Theta_h - \Theta_c)},$$

$$SEER = \frac{\eta_{II} (\Theta_c + 273.2)}{(\Theta_h - \Theta_c)},$$

where:

- $\theta_h$ is the absolute temperature of the hot source;
- $\theta_c$ is the absolute temperature of the cold source;
- $\eta_{II}$ is the second law efficiency.

DesignBuilder cannot automatically derive the size of the GSHP, thus the following procedure was applied:

- The building design thermal loads (both for heating and cooling) are evaluated;
• A heat pump type from the DesignBuilder database is selected, taking into account the design thermal loads for both heating and cooling. Alternatively, it is possible to model a different kind of heat pump;
• The number of vertical probes is evaluated.

For the evaluation of the correct size of the heat pump, the thermal power necessary for handling the treated ventilation external air (“primary air”) was also considered. In the examined case study, this is about 6 kW in summer; moreover, considering a ground that dissipates 50 W/m of thermal energy, the number of 4 vertical U-bend probes was obtained for both Milan and Palermo.

Regarding energy analysis, the primary energy is evaluated: the considered conversion factors are 2.2 for electricity and 1.05 for natural gas. To calculate the CO\(_2\) emissions, the used procedure is explained in Section 4 (Results and discussion—CO\(_2\) emissions) [44].

### 2.2. Procedure to Obtain an NZEB

Regarding the satisfaction of the energy balance, there are currently no specific requirements for the NZEB target. The Italian law strictly defines only nearly zero energy building (nZEB), by means of the D.M. 26 June 2015 [45]. Therefore, according to this decree, the following requirements have been satisfied for the building-system complex examined (the first three refer only to the building envelope, the fourth refers to only the building energy systems, the last to the entire building-system complex):

• Building average heat transfer coefficient: \(H'_T \leq \) reference value (W/m\(^2\)K);
• The ratio between the summer equivalent solar area of the windows and the useful walking surface: \(A_{sol, equiv, summer}/A_{walking\ surface} \leq \) reference value (-);
• Energy performance indexes for the building envelope in winter and summer: \(E_{P_{H, nd}}, E_{P_{C, nd}} \leq \) reference values (kWh/m\(^2\)y);
• Efficiencies of the building energy systems (H for heating, C for cooling, DHW for domestic hot water): \(\eta_H, \eta_C, \eta_{DHW} \geq \) reference values (-);
• Global energy performance index of the building-systems complex: \(E_{P_{glob, tot}} \leq \) reference value (kWh/m\(^2\)y).

In this way it was verified that the case study building is a nZEB; subsequently, in order to obtain an NZEB, an electricity production system from renewable sources (photovoltaic solar modules) is designed and inserted on the roof of the building. The global capturing surface of these modules is evaluated for the following different cases: GSHP, air source heat pump, condensing boiler plus chiller. Thereby, it is possible to estimate whether the GSHP would allow to achieve the NZEB target with a photovoltaic surface significantly smaller compared to the other solutions.

The derivation of the energy balance of a NZEB can be performed in different ways [6,46,47]. In this work, the control volume that coincides with the complete building is chosen, and therefore the building-systems energy demand and the energy produced by renewable sources (kWh/m\(^2\)y) are considered in the energy balance:

\[
E_{demand} - E_{produced\ by\ renewables} = 0 \quad (8)
\]

This energy balance must be satisfied to obtain a NZEB. To this end, an accurate design of the building-system complex is required to minimize the energy demands. Therefore, it was determined which of the analysed solutions (GSHP, air source heat pump, condensing boiler plus chiller) has the minimum energy requirement to facilitate the achievement of the NZEB objective.

The Figure 1 shows the general design and computational workflow followed in this study for obtaining the NZEB target.
3. Case Study

The pilot building is used as a bed and breakfast and is virtually located in two Italian towns having different climates (Table 2): Palermo (South Italy), with mild winters and very hot summers; Milan (North Italy), with cold winters and hot summers.

Table 2. Geographic and climatic conditions of the selected towns, from ASHRAE [37] and DPR 412/93 [48].

| Town    | Degrees-Day (*) | Climatic Zone for Heating (*) | Latitude   | Longitude   | Outdoor Design Temperature       |
|---------|-----------------|--------------------------------|------------|-------------|----------------------------------|
| Milan   | 2404 K-day       | E                              | 45°28'36" N | 9°10'53"E  | 35.1 °C, −4.9 °C                 |
| Palermo | 751 K-day        | B                              | 38°6'43"N  | 13°20'11"E | 33.8 °C, 6.6 °C                  |

(*) according to DPR 412/93 (1993) [48].

The building is characterised by two floors, global area of 310 m², and global volume of 900 m³. Accurate design of the building and passive design rules are applied in order to achieve the NZEB target: considering the sun position, the living zone is placed on the south side in order to maximize solar gains in winter, while the service rooms and sleeping zone are placed on the north side (Figures 2 and 3). Moreover, the windows are designed in order to optimise natural ventilation. A compact form of the building is chosen, so the surface-to-volume ratio is equal to only 0.20 m⁻¹. Low values of unitary thermal transmittance of the building envelope components are used (Table 3), particularly for the coldest town (Milan), in order to minimise the thermal losses in winter.

Table 3. Unitary thermal transmittance of the case study building envelope (W/m²K).

| Town    | U_{Walls} | U_{Roof} | U_{Floor} | U_{Windows} |
|---------|-----------|----------|-----------|-------------|
| Milan   | 0.24      | 0.21     | 0.23      | 1.20        |
| Palermo | 0.42      | 0.33     | 0.39      | 2.05        |

Table 4 reports the design thermal loads of the building (for both heating and cooling conditions), calculated by the software, while Table 5 shows the values of the seasonal average energy efficiency for the three compared systems.
Town Volume Thermal (Heating and Cooling) Loads

| Winter Conditions | Summer Conditions |
|-------------------|-------------------|
| m3/kW            | m3/kW            |
| Palermo          | 900              | 12              |
|                  | 10               | 13              |
|                  | 22              | 21              |
|                  | 24              | 23              |

Figure 2. Three-dimensional model of the case study building.

Table 5. Seasonal average energy efficiency for the analysed solutions.

| Solution                  | Boiler Efficiency | or SCOP S | SEER | Boiler Efficiency | or SCOP S | SEER |
|---------------------------|-------------------|-----------|------|-------------------|-----------|------|
| GSHP (ground-to-water heat pump) | 4.80             | 7.00      | 6.20 | 5.60              | 5.90      | 5.60 |
| Air source heat pump (air-to-water heat pump) | 4.10             | 4.80      | 4.80 | 4.90              | 4.90      | 4.90 |
| Condensing boiler + air-cooled chiller | 0.90             | 4.80      | 0.90 | 4.90              | 4.90      | 4.90 |

Figure 3. Plan of the ground floor and first floor of the case study building.
Table 4. Design thermal loads of the case study building for both heating and cooling.

| Town      | Volume | Thermal (Heating and Cooling) Loads |
|-----------|--------|------------------------------------|
|           |        | Winter Conditions                  | Summer Conditions |
|           |        | kW       | W/m³       | kW       | W/m³       |
| Palermo   | 900    | 10       | 12         | 22       | 24         |
| Milan     |        | 12       | 13         | 21       | 23         |

Table 5. Seasonal average energy efficiency for the analysed solutions.

|                      | Milan          | Palermo        |
|----------------------|----------------|----------------|
| Boiler Efficiency or SCOP | 4.80          | 6.20           |
| SEER                 | 7.00           | 5.60           |
| Air source heat pump (air-to-water heat pump) | 4.10           | 4.80           |
| Boiler Efficiency or SCOP | 4.80           | 4.90           |
| SEER                 | 4.80           | 4.90           |
| Condensing boiler + air-cooled chiller | 0.90           | 0.90           |
| Boiler Efficiency or SCOP | 4.80           | 4.90           |
| SEER                 | 4.80           | 4.90           |

Each of the analysed thermal energy generators is connected to fan-coil units located inside the rooms and to an air handling unit (AHU) for primary air.

The design thermo-hygrometric conditions are as follows:

- indoor air: temperature of 20 °C for winter and 26 °C for summer, relative humidity of 50% for both winter and summer;
- supply primary air: temperature of 20 °C for winter and 12 °C for summer.

Referring to the heating mode, different working programs are selected for the two analysed towns, according to DPR 412/93 [48]:

- Palermo (climatic zone: B): from 1 December to 31 March (6:00–9:00 a.m., 6:00–11:00 p.m.—total of 6 h per day);
- Milan (climatic zone: E): from 15 October to 15 April (5:00–9:00 a.m., 12:00 a.m.–3:00 p.m., 5:00–12:00 p.m.—total of 14 h per day).

Referring to the cooling mode, the operational programs are fixed as follows:

- Palermo: from 1 June 1 to 30 September (11:00 a.m.–4:00 p.m., 6:00–10:00 p.m.—total of 9 h per day);
- Milan: from 1 June to 30 September (11:00 a.m.–3:00 p.m., 6:00–10:00 p.m.—total of 8 h per day).

The production of domestic hot water (DHW) is obtained by means of solar thermal collectors (five for Milan, four for Palermo) and a dedicated air-to-water heat pump (COP = 2.5), while the consumption rate is considered to be 2.5 L/m²day.

LED devices with a linear control system are used as the lighting system (2.5 W/m²-100 lux). The design values of the illuminance are 300 lux in bedrooms and 500 lux in common spaces.

Few other electrical devices exist, so a range of only 1–4 W/m² is considered.

4. Results and Discussion

4.1. Energy Analysis

The primary energy demand for the different proposed solutions, divided for energy uses, is shown in Figures 4 and 5, for Palermo and Milan, respectively.
The production of domestic hot water (DHW) is obtained by means of solar thermal collectors (five for Milan, four for Palermo) and a dedicated air-to-water heat pump (COP = 2.5), while the consumption rate is considered to be 2.5 L/m²·day.

LED devices with a linear control system are used as the lighting system (2.5 W/m² - 100 lux). The design values of the illuminance are 300 lux in bedrooms and 500 lux in common spaces.

Few other electrical devices exist, so a range of only 1–4 W/m² is considered.

### 4. Results and Discussion

#### 4.1. Energy Analysis

The primary energy demand for the different proposed solutions, divided for energy uses, is shown in Figures 4 and 5, for Palermo and Milan, respectively. The aim is to highlight the primary energy saving obtained when using the GSHP instead of the air source heat pump or the condensing boiler coupled to the chiller.

For Palermo, the following percentage savings can be obtained from the values of Figure 4: the use of GSHP involves an energy saving of 15% for heating plus cooling when compared to the air source heat pump (23% with reference to only heating, 12% for only cooling); the above mentioned saving is 38% when compared to the case with boiler plus chiller.

Regarding the entire yearly demand of primary energy for Palermo, Figure 6 shows that the GSHP results in a 5% saving compared to the air source heat pump and 16% compared to the solution with boiler plus chiller.

**Figure 4.** Primary energy demand (kWh/m²·y) for the three different proposed systems in the case of Palermo.

**Figure 5.** Primary energy demand (kWh/m²·y) for the three different proposed systems in the case of Milan.

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Regarding the entire yearly demand of primary energy for Palermo, Figure 6 shows that the GSHP results in a 5% saving compared to the air source heat pump and 16% compared to the solution with boiler plus chiller.
boiler plus chiller. The yearly demand of electric energy varies from 6131 kWh/y (20 kWh/m²y) related to the use of the air source heat pump, to 5810 kWh/y (18.7 kWh/m²y, i.e., −5%) related to the use of the GSHP. Figure 7 reports the pie chart relative to the energy requirements in the case of the GSHP for Palermo.

![Figure 7. Pie chart relative to the energy requirements in the case of the GSHP for Palermo.](image)

With reference to Milan (cold winters), from the values of primary energy demand reported in Figure 5, the GSHP involves the following saving on the primary energy: 23% for heating plus cooling compared to the air source heat pump (19% for solely heating, 34% for cooling); 55% for heating plus cooling compared to boiler plus chiller.

Regarding the entire yearly demand of primary energy for Milan, Figure 8 shows that the GSHP involves a 10% saving compared to the air source heat pump and 33% compared to the solution with the condensing boiler plus chiller. The yearly demand of electric energy varies from 8171 kWh/y (26.4 kWh/m²y) related to the use of the air source heat pump, to 7316 kWh/y (23.6 kWh/m²y, i.e., −10%) related to the use of the GSHP. Although the percentage saving of total primary energy between the GSHP and the air source heat pump seems to be small, it is useful to highlight that the total primary energy consumption is equal to 57 kWh_p/m²y. According to the New Building Institute of
the U.S. [22], that value identifies an NZEB, and this result in a cold climate such as Milan is reached only by using a GSHP as a thermal energy generator.

![Figure 8](image_url)

**Figure 8.** Entire yearly demand of primary energy (kWh/m$^2$y) for the three analysed solutions in the case of Milan.

Figure 9 reports the pie chart relative to the energy requirements in the case of GSHP for Milan.

![Figure 9](image_url)

**Figure 9.** Pie chart relative to the energy requirements in the case of GSHP for Milan.

As shown in Figures 6 and 8, the entire primary energy requirement for both of the localities is low: 45–54 kWh/m$^2$y for Palermo and 57–85 kWh/m$^2$y for Milan.

Clearly, a significant primary energy saving is achieved for heating plus cooling with the use of the GSHP compared to the air source heat pump (15–23%), or to the boiler plus chiller (38–55%), mainly for the colder climate of Milan (55%). Similar results are found in Garcia-Céspedes et al. [49]: in fact, in this paper the savings related to a GSHP are also around 20% compared with a traditional heat pump. Furthermore, according to an ENEA report [50], the hotels in Italy, including bed and breakfasts, have an electricity consumption of 30–60 kWh/m$^2$ for southern Italy (Palermo) and 30–90 kWh/m$^2$ for northern Italy (Milan); the analysed building, designed to be a NZEB, consumes between 24 and 26 kWh/m$^2$ of electricity.

At present, fundamental topics are sustainability and attention to the environment. In fact, climate change is accelerating due to greenhouse gas emissions. The European Union has the objective to reduce gas emissions of 20% by 2020 and to obtain total decarbonization by 2050 [44]; all of the actions tend to an energy-efficient and low-carbon economy. One of the first steps in reducing CO$_2$ emissions is to lower energy consumption for heating and cooling by using increasingly efficient technologies.
For this reason, as an appendix of the energy analysis, a simplified analysis of the CO₂ emissions was performed. This is not a Life Cycle Assessment (LCA) or a cradle-to-grave analysis, but only an investigation to compare the reduction of CO₂ emissions related to the use of the building energy systems (so only during the useful life of the building), comparing the case of considering a GSHP with the other two system solutions. The reduction in CO₂ emissions is assessed with reference to both heating only and global energy used during the year.

To calculate the CO₂ emissions of the condensing boiler, the primary energy is multiplied by the standard emission factor of greenhouse gases referring to natural gas, equal to 0.202 kgCO₂/kWh [44]. To obtain the CO₂ emissions from electric heat pumps or a chiller, the final electric energy is multiplied by the standard emission factor of greenhouse gases related to electricity, equal to 0.483 kgCO₂/kWh [44].

As can be seen in the Table 6, a significant reduction of CO₂ emissions using the heat pumps instead of a condensing boiler (plus chiller) is obtained. This reduction of CO₂ emissions is 60% and 67% for only heating for Milan and Palermo, respectively, using a GSHP instead of the condensing boiler plus chiller (Figures 10 and 11). CO₂ emissions reduction relating to global energy consumption is 33% for Milan and 16% for Palermo comparing the GSHP to the condensing boiler plus chiller.

Table 6. Annual CO₂ emissions for Milan and Palermo referred to only heating and global energy consumption.

| Energy Vector | Heating | CO₂, heating Emissions | Energy Vector | Total Consumption | CO₂,total Emissions |
|---------------|---------|------------------------|---------------|------------------|---------------------|
| Milan         | '-'     | kWh                    | kWh           | '-'              | kWh                |
| Condensing Boiler + Chiller | natural gas | 12,488                | natural gas   | 12,488           | 5272               |
| Air Source Heat Pump | electricity | 2740                  | electricity   | 8171             | 3947               |
| Ground Source Heat Pump | electricity | 2220                  | electricity   | 7316             | 3534               |
| Palermo       | '-'     | '-'                    | '-'           | '-'              | '-'                |
| Condensing Boiler + Chiller | natural gas | 3147                  | natural gas   | 3147             | 3344               |
| Air Source Heat Pump | electricity | 590                   | electricity   | 6131             | 2961               |
| Ground Source Heat Pump | electricity | 457                   | electricity   | 5811             | 2807               |

Figure 10. CO₂ emissions reduction for different solutions in Palermo.
The CO₂ emissions reduction comparing the GSHP to the air source heat pump is also significant (19–23%) referring to only heating consumption. Conversely, when considering the global energy consumption, this reduction is only 5–11%.

4.2. NZEB Target

Tables 7 and 8 report the yearly energy balance and the number of solar thermal and photovoltaic modules necessary to obtain a zero energy balance between produced energy by renewables and consumed energy by the building, in the case of Palermo and Milan, respectively, considering the three proposed HVAC solutions and a useful surface on the roof of the building to install thermal and photovoltaic solar panels equal to 90 m². The following procedure was considered to obtain a NZEB:

- For the cases characterized by solely electric energy demand (GSHP and air source heat pump), the yearly electric energy demanded by all the systems of the building is calculated: it must be balanced by the yearly electric energy obtained by the photovoltaic modules (320 Wₚₑ𝐚ᵏ per module);
- For the case characterized by both electric energy and natural gas demand (boiler plus chiller), the yearly electric energy demanded by all the systems of the building must be balanced by the yearly electric energy obtained by the photovoltaic modules, while the yearly thermal energy related to the natural gas demanded by the boiler (3147 kWh for Palermo) is related to primary energy (3304 kWhₚₑᵣ), as suggested in [51,52], and this must be balanced by the annual electric energy obtained by the photovoltaic modules (note that, in the case of photovoltaic modules, this electric energy is equal to the corresponding primary energy).

In the case of Palermo (Table 7) when using the GSHP, 27 photovoltaic modules are necessary to obtain an NZEB, while 42 PV modules are needed when using a condensing boiler plus chiller, and 28 when using an air source heat pump. In a hot climate such as that of Palermo, both the definition of an NZEB obtained satisfying the energy balance dictated by the EPBD [2] and the definition of an NZEB suggested by the New Building Institute of U.S. reported in [22] are verified; however, using a GSHP between 5 and 92% (compared to the other two system configurations) of capturing area to be used for photovoltaics is saved.
Table 7. Yearly energy balance for obtaining a NZEB in the case of Palermo.

| PALERMO         | Photovoltaic Panels (320 Wp Per Panel) Production 431 kWh/Year |
|-----------------|----------------------------------------------------------------|
|                  | n° of Solar Panels | Annual Energy Requirements | Primary Energy Conversion Factor | n° of Panels | Reduction of Panel | Annual Energy Production | Photovoltaic Surface | Maximum Available Area for Photovoltaic Modules | NZEB Balance [2] | NZEB Definition [22] |
| Boiler + chiller | 4                  | 3469                       | 1.05                           | 8.0         | 92               | 3469                       | 42               | 90                                               | ✔                     | ✔                     |
| Air-to-water heat pump | 6131            | -                          | 14                             | 5           | 6131             | 28                          | 27               |                                                   | ✔                     | ✔                     |
| Ground source heat pump | 5811            | -                          | 13                             | -           | 5811             | 27                          |                   |                                                   | ✔                     | ✔                     |

Table 8. Yearly energy balance for obtaining a NZEB in the case of Milan.

| MILAN           | Photovoltaic Panels (320 Wp Per Panel) Production 352.2 kWh/Year |
|-----------------|----------------------------------------------------------------|
|                  | n° of Solar Panels | Annual Energy Requirements | Used Primary Energy Conversion Factor | n° of PV Panels | Reduction of Panel | Annual Energy Production | Photovoltaic Surface | Maximum Available Area for Photovoltaic Modules | NZEB Balance [2] | NZEB Definition [22] |
| Boiler + chiller | 5                  | 13,113                     | 1.05                           | 37           | 61               | 13,113                     | 105              | 90                                               | x                     | x                     |
| Air-to-water heat pump | 8171           | -                          | 23                             | 10           | 8171             | 46                          | 42               |                                                   | ✔                     | x                     |
| Ground source heat pump | 7316           | -                          | 21                             | -            | 7316             | 42                          |                   |                                                   | ✔                     | ✔                     |
With reference to Milan (Table 8), this town has a greater energy demand due to winter heating, therefore the energy saving induces a significant decrease of the photovoltaic surface: when using the GSHP, 21 PV modules are necessary to reach the NZEB target, versus 23 PV modules in the case of air source heat pump and 52 modules in the case of boiler plus chiller (the worst case), i.e., a reduction of 10 and 61% in the photovoltaic surface. In the case of the continental climate of Milan, it is not possible to satisfy the NZEB target in the case of a condensing boiler plus chiller as the photovoltaic surface needed to obtain a zero energy balance of (105 m$^2$) is greater than the surface available for installation (90 m$^2$). Furthermore, based on the definition of an NZEB reported by the New Building Institute of U.S. [22], the only case in which the primary energy consumption limit value of 57 kWh/m$^2$ is respected is that with the GSHP.

In Italy, there are currently specific legislative prescriptions to define an nZEB, but not an NZEB. Therefore, for all the analysed cases, the verification of the minimum requirements for an nZEB was satisfied using the TERMOLOG software [53]. Moreover, the percentage was obtained of renewable energy exploited by the various examined technologies: considering both the towns, 81% is related to the use of the GSHP, 75–76% for the air source heat pump, and 63–64% for the solution with boiler plus chiller.

### 4.3. Technical-Economic Analysis

For the three analysed HVAC configurations, the investment costs were evaluated [54]; then, discounted payback (DPB) periods were calculated, as reported in Table 9.

| PALERMO | MILAN |
|---------|-------|
| **Ground Source Heat Pump Compared to Boiler + Chiller** | | |
| Additional Cost | Saving | DPB | Additional Cost | Saving | DPB |
| (€) | (€) | (years) | (€) | (€) | (years) |
| 2273 | 254 | 14 | 2084 | 825 | 3 |

| **Ground Source Heat Pump Compared to Air Source Heat Pump** | | |
| Additional Cost | Saving | DPB | Additional Cost | Saving | DPB |
| (€) | (€) | (years) | (€) | (€) | (years) |
| 3123 | 72 | >useful life | 3684 | 192 | >useful life |

To define the energy costs, the calculation was made by referring to the values recommended by Eurostat’s “Statistics Explained” [55], i.e., an average value of 0.225 €/kWh for electricity consumption and 0.100 €/kWh for natural gas.

From an economic point of view, the comparison between the GSHP versus boiler plus chiller is the most convenient if it refers to a continental climate (Milan), as the energy saving related to the GSHP is relevant. In fact, the DPB is only 3 years for Milan, while for Palermo (mild climate) it is around 14 years (a not recommended value).

The GSHP is less convenient when compared to the air source heat pump: both for Milan and for Palermo, the DPB is more than the useful life, so the air source heat pump is economically more convenient than the GSHP. However, it is noteworthy that the air source heat pump may malfunction in cold climates such as Milan; thus, it may not always satisfy the user when very low external temperatures occur.

### 5. Conclusions

This paper investigates through an energy assessment the contribution that the geothermal heat pump can have on the reduction of the surface to be used for photovoltaics in order to obtain an NZEB...
with only on-site renewable sources. These assessments are carried out by comparing the GSHP with a common system—i.e., a condensing boiler coupled to a chiller—and with a more energy efficient system, namely, an air source heat pump.

It was shown that when using the GSHP, compared to the other systems, the NZEB target is obtained by using a smaller photovoltaic surface. Furthermore, although the comparison is also carried out with a performing technology such as the air-to-water heat pump, the GSHP is the only system that allows annual primary energy consumption equal to or lower than 57 kWh/m² to be obtained for both of the analysed climatic zones. This is an important result since this value in the current scientific community is taken as a reference to define an NZEB. These are the main innovative aspects obtainable from this paper, that is, the optimal coupling of a GSHP with a photovoltaic system to obtain the NZEB target, minimizing the number of photovoltaic panels.

In more detail, it was found that the use of the GSHP, compared with the two other systems, allows considerable energy savings for heating and cooling (15–38% for Palermo and 23–55% for Milan).

Moreover, a significant reduction of CO₂ emissions is obtained when using a ground source heat pump instead of a condensing boiler (plus chiller). This reduction

- is 60 and 67% when considering only heating energy requirements for Milan and Palermo, respectively;
- is instead 33% for Milan and 16% for Palermo in reference to global energy consumption.

The CO₂ emissions reduction comparing the GSHP and the air source heat pump is also significant (19–23%) regarding to heating only consumption. Conversely, when considering the global energy consumption, this reduction is only 5–11%.

Regarding the photovoltaic surface to obtain a NZEB, the use of a GSHP instead of a condensing boiler coupled to a chiller leads to reductions of 92% for Palermo and 61% for Milan. These reductions are 5% for Palermo and 10% for Milan when comparing the GSHP with a more efficient technology such as the air source heat pump. The obtained results in the context of the NZEB is very important, as in highly urbanized contexts the space to allocate the production energy systems from renewable sources is often small and even 10% of surface savings can make the difference to obtain the NZEB target. In fact, the results showed that in the case of a continental climate such as Milan, in which the winter energy demand is predominant, it is not always possible to satisfy the NZEB target due to insufficient roof surface.

Beyond satisfying the energy balance, an energy demand limit value was considered to classify a building as an NZEB: it is suggested by the New Building Institute of the U.S. and is equal to 57 kWh/m². If this limit value is considered, the building in question can be considered an NZEB for both climatic conditions only by using the GSHP.

Finally, referring to the energetic-economic analysis, the discounted payback (DPB) period for the GSHP is about 3 years for Milan and 14 years for Palermo when compared to the configuration with boiler plus chiller, while it is more than the useful life when compared to an air source heat pump.

Therefore, the air source heat pump seems more convenient than the GSHP from an economic point of view. However, it should be noted that the air source heat pump, especially in cold climates (Milan), can be affected by malfunctions in the case of very low external temperatures, when it may sometimes not satisfy the user.

Clearly, for the analysed cases, in order to obtain an NZEB, the ground source heat pump (compared to the common configuration with a condensing boiler coupled to a chiller and to the solution with the air source heat pump) has the highest performance from an energy point of view, but is still too expensive. Therefore, from an economic point of view (discounted payback period), it is really convenient only for continental climates (Milan) when compared to the solution with a condensing boiler coupled to a chiller.
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Nomenclature

| Term     | Description                      |
|----------|----------------------------------|
| AHU      | air handling unit                |
| COP      | coefficient of performance       |
| CTFM     | conduction transfer function mode|
| DPB      | discounted payback               |
| EPBD     | energy performance building directive|
| GSHP     | ground source heat pump          |
| NZEB     | net zero energy building         |
| nZEB     | nearly zero energy building       |
| SCOP     | seasonal coefficient of performance|
| SEER     | seasonal energy efficiency ratio  |
| ZEB      | zero energy building              |

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