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Comparative Analysis of Ground Source and Air Source Heat Pump Systems under Different Conditions and Scenarios

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Abstract: The current energy context demands the use of environmentally friendly solutions that contribute to the displacement of traditional fossil fuels. In this regard, heat pumps have become an important tool in the decarbonization of the heating and cooling energy system. With the aim of providing new information in the field, this research is conducted to analyze the suitability of a Ground Source Heat Pump (GSHP) and an Air Source Heat Pump (ASHP) in two different scenarios. Systems are designed to cover the heating needs of a building placed in a cold climate area, characterized by being in a thermally and geologically favorable formation (Case 1), and in a mild climate location where the geology is not so appropriate for the thermal exchange with the ground (Case 2). Results highlight the need to perform an exhaustive study of the subsoil and the external conditions of the area for a reliable selection. In Case 1, the ASHP option is discarded due to the demanding outdoor air requirements that rocket the operating costs of the system. In Case 2, both solutions are viable, with the geothermal alternative preferred if the initial investment can be assumed, providing economic advantages from the 17th year of the system operation.

Keywords: heating energy system; GSHP; ASHP; subsoil; geology; external air conditions

Citation: Blázquez, C.S.; Nieto, I.M.; García, J.C.; García, P.C.; Martín, A.F.; González-Aguilera, D. Comparative Analysis of Ground Source and Air Source Heat Pump Systems under Different Conditions and Scenarios. *Energies* **2023**, *16*, 1289. https://doi.org/10.3390/en16031289

Academic Editor: Adrián Mota Babiloni

Received: 20 December 2022
Revised: 18 January 2023
Accepted: 23 January 2023
Published: 25 January 2023

1. Introduction

Economic growth, directly linked to world population growth, is one of the main causes of the global energy consumption increase [1]. In this scenario, the world energy supply is still alarmingly dependent on the use of fossil fuels, which inevitably translates into unacceptable emissions of Green House Gases (GHG) [2]. With the final aim of mitigating the devastating effects of these traditional energy sources, renewable energies arise as a significant mechanism for coping with climate change. In this way, wind, solar or hydroelectric power systems (usually the most used) are frequently incorporated by states as renewable solutions to reduce the vulnerability of electricity systems and fossil fuels dependence [3].

Focusing on heating and cooling energy applications, in Europe the building sector is responsible for 40% of the energy consumption and 36% of CO_2 emissions; however, the housing sector is the key for reducing global GHG emissions with a saving potential up to 90% by 2050 [4]. In this context, the implementation of renewable energies for reducing these emissions is considered inherent to achieving European objectives [5].

For the above, beyond the commented renewable technologies, geothermal energy is slowly increasing in the European context, constituting a feasible option to assist in reaching the Paris Agreement to limit the atmospheric temperature increase 2 °C or less [6], and the objectives of the Roadmap 2050 to control the GHG emissions by 20% below 1990 levels by 2020 and by 80–95% by 2050 [7]. In this sense, the European Union funded with a total of 90 million euros the development of geothermal technologies during the period of 2014–2018 within the Horizon 2020 Framework Program [8]. Other additional European policies support the development of renewable heating and cooling solutions with great expectations for shallow geothermal energy. Furthermore, the new Horizon Europe Framework Program conceived for 2021–2027 strongly focuses on the mitigation of climate change in which shallow geothermal resources play a significant role [9].

As deduced from the above, over the last few years, a special focus has been set on the mentioned shallow geothermal energy, exploited by Ground Source Heat Pumps (GSHP) for moving forward the decarbonization of the residential sector. Despite this fact, and the high potential of this energy, only around 2% of renewable heating and cooling is produced in Europe through these systems [10]. The reasons of this low geothermal use are mainly due to non-technological barriers, such as upfront costs, legal issues, or low visibility and awareness for end users [11]. In this regard, different actions are required to face all these issues, from regional and national measures but also through novel research aimed at optimizing this potential but still not spread enough solution [12–15].

Derived from the previous barriers, especially the investment that is initially required in most of the GSHP building installations, Air Source Heat Pumps (ASHP) are increasingly growing in the heating and cooling sector, becoming the most common form of heat pumps in Europe [16]. These devices will probably play an important role as building heating is electrified, especially in urban areas. However, ASHP systems are not always the most advantageous alternative, meaning a non-recommended solution in those scenarios in which the external conditions cause high operating costs.

1.1. Heat Pumps Overview

As mentioned above, heat pumps have become one of the most influential technologies in future sustainable energy development. These devices are capable of transferring heat from a natural environment such as the ground, air, or water, as well as from other sources of industrial or domestic waste. They move heat from a region of low temperature to another of higher temperature (or inverted) by using a small amount of electricity, being used for both space cooling and heating and for water heating as Domestic Hot Water (DHW).

Heat pump efficiency is defined by the comparison of the amount of heat energy provided by the heat pump and the amount of energy that it consumes, which is in turn expressed as the Coefficient Of Performance (COP), the ratio of the amount of heating/cooling in kilowatts delivered by a heat pump, Q, to the kilowatts of power consumed by the heat pump, W. Analogously, in the cooling mode, the Energy Efficiency Ratio (*EER*) is used to express the relation between the heat extracted from the space and the electricity consumed by the heat pump. In fact, one of the main advantages attributed to these systems is the high COP and, therefore, the reduced electrical consumption associated with their use. The value of this COP depends on the conditions of the installation, but it is especially high in GSHP systems and in those hybridizations of heat pumps (both GSHP and ASHP) with other renewable systems, such as solar collectors or photovoltaic panels [17,18].

1.1.1. Geothermal Heat Pumps

Geothermal heat pumps or ground source heat pumps exploit the Earth's heat through heat exchangers buried in the ground. This makes it possible to increase heat extraction but at the same time makes the global heating system more expensive and disruptive. Two main categories are found in these solutions, the water-to-air (most used in office buildings) system, which uses water for the thermal exchange with the ground and air for heating the space and the water-to-water (especially used in the residential sector) alternative that applies water for both purposes. Within the global geothermal systems, two different configurations are frequently found; open-loop systems (also including surface-water heat pumps), which extract water directly from a nearby aquifer or river through an extraction well and return it after passing through the installation through a second injection well. In turn, there are closed-loop exchange systems that are based on the use of a sealed exchanger that extracts heat from a rocky or soil underground source. These pipes can be arranged horizontally, at depths of 1–2 m, although the most common schema is the use of vertical boreholes with depths between 100–150 m, which significantly increase the thermal exchange with the ground due to their capability to exploit the thermal resource at a constant temperature during the whole year and the higher temperature values achieved at those levels.

The heating capacity of these systems is directly related to the size of the buried thermal exchangers, so it is vital to perform a correct sizing of the system to avoid thermal comfort loss during the progressive operation of the installation [19]. In this sense, it is especially important to perform an in-depth study of the subsoil for defining the predominant geological formations in depth and their capacity for thermal exchange with the components of the geothermal system [20,21].

1.1.2. Air Source Heat Pumps

Air source heat pump systems are based on using the difference between the indoor and outdoor air temperatures to heat/cool a certain space. These devices are commonly divided into two main varieties: air-to-air and air-to-water systems.

The first category directly heats the air of a room by the use of a wall-mounted box (different indoor units can be connected to the compressor as multi-split systems, to increase the number of rooms to be heated). As the GSHPs, most of these systems are reversible units, performing both heating and cooling.

On the other hand, air-to-water heat pumps are integrated into a hydronic central heating system that aims at providing the building heating and hot water. Beyond the outdoor compressor, split systems also need a control unit and a compact heat exchanger placed next to the hot-water cylinder to transfer heat from the refrigerant.

ASHPs are the most widely used heat pumps and are present in numerous countries, being often preferred in moderate climates and in those existing houses located in high-density urban areas with the limited surrounding land. Air-to-air heating alternatives are widely distributed across southern Europe and Asia, where the climate conditions allow their use for both heating and air conditioning [22–25].

Reviewed literature attributes GSHPs with several advantages in terms of higher energy efficiency, lower life cycle cost and less impact on the environment, all coupled with greater system reliability and other practical reasons. In short, GSHP systems are recommended in those cases of new construction buildings, with high energy demands and where the user can face high or moderate initial investments. GSHPs are also considered a priority in climates with great seasonal temperature variation. Regarding ASHPs, these are suited when the local climate is mild, when the land availability does not allow the earth connection or when the user prioritizes shorter payback periods [26,27]. However, most of these statements are variable in function on the specific case under study and in particular, the climate conditions where the space is located [28,29].

Another aspect to consider is the Urban Heat Island (UHI) effect and its relation with the use of both GSHP and ASHP systems. Published research highlights the role of these solutions to remove the accumulated heat from urban area and the significant mitigation of this phenomenon when they are implemented. Results also declare a net superiority of the GSHP compared to the ASHP, especially in heating mode when open geothermal loops are used on existing aquifers [30]. In the case of ASHP technologies, it is well known that they contribute to alleviating the urban heat island effect (heat is absorbed from the outdoor air at the same time that cold exhaust is emitted), showing substantial cooling effects that achieve to decrease the air temperatures of the site when different heat pumps are operating in cooling mode [31].

Despite the general rules previously mentioned, it is still a reality that in numerous cases the user does not have the necessary information to determine what type of heat pump is the most appropriate for the particular characteristics of the installation to be heated. Since most of the existing research has focused on the analysis of heating and cooling in industrial energy systems, there is a clear lack of precise information in this regard adapted to the domestic sector. For the above, this research intends to evaluate the most suitable heat pump alternative in different scenarios and climatic zones. The objective is to provide new information on the performance of each system under different conditions and to contribute to future decision-making that, in turn, helps to decarbonize the energy system in an optimized way adjusted to the needs of the assumption. The main novelty of the work is the inclusion of real data of the study areas, based on in situ prospecting tests, that allow characterizing in detail the conditions of the locations to better predict the behavior of both GSHP and ASHP systems and perform an improved and justified decision. The structure of the paper is as follows: Section 2 includes the description of the methodology and cases under study, Section 3 presents the main results of the work and, finally, Sections 4 and 5 address the discussion and conclusions extracted from it.

2. Methodology

As mentioned in the introductory section, this research is based on the design of a ground source and air source heat pump (air-to-water) system in different preselected study areas with the final aim of establishing the most appropriate solution in each location from a technical, environmental and economical point of view. As can be observed in the workflow included in the following Figure 1, after the selection of the areas under study, both heat pump systems will be calculated for each assumption after the corresponding evaluation and characterization of the ground (for GSHP) and the external conditions. The design of each system will finally allow us to define the most suitable installation according to the particularities of each location.

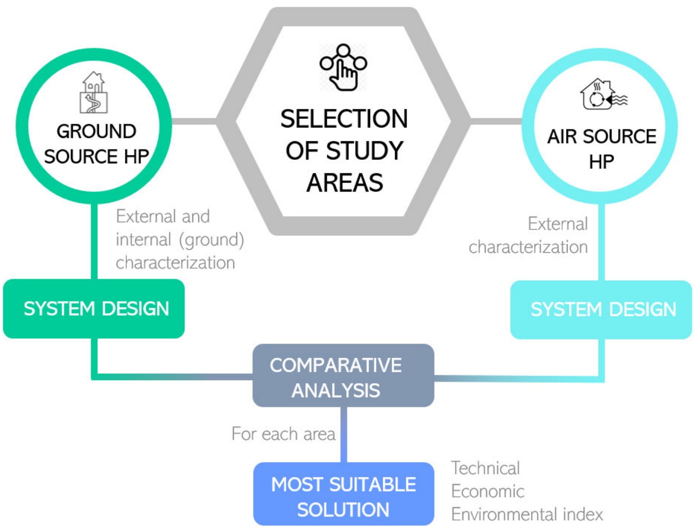

Figure 1. Workflow followed in the present research.

2.1. Systems Description

With the objective of covering the required heating needs assumed in this work, two standard ASHP and GSHP systems are considered. Both ASHP and GSHP systems undergo the thermodynamic processes described in Figure 2 [32].

For the cycle described above, R161 and R41 could be suitable for being used as the refrigerants used in the heat pump operation selected in this work. This selection is based on the thermophysical properties that are suitable enough to use as working fluid in the cycles of the heat pumps systems. In addition, considering the environmental parameters of these refrigerants, ozone depletion potentials of them are equal to zero with acceptable values of global warming potentials, 97 for R41 and 12 for R161 [33]. More information about the basic properties of these refrigerants is included in Table 1.

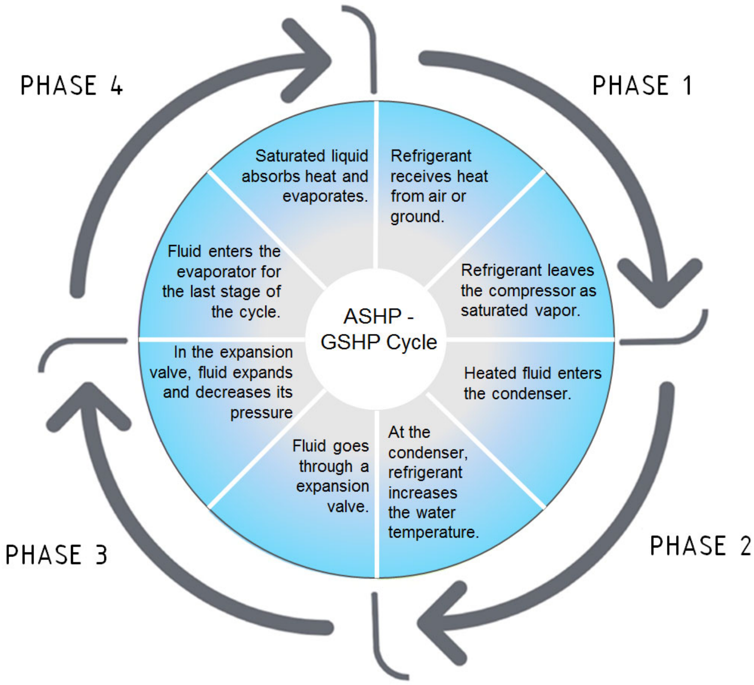

Figure 2. Schematic view of the ASHP and GSHP systems.

Table 1. Main properties of the refrigerants considered in this research [34].

Refrigerant	R161	R41
Official name	Fluoroethane	Fluoromethane
Molar mass (g/mol)	48.06	34.03
Critical temperature (°C)	102.1	44.13
Boiling point (°C)	−37.54	−78.31
Critical pressure (bar)	50.46	58.97

2.2. Study Cases

As mentioned throughout this research, the objective is to analyze the most appropriate heat pump solution in different scenarios. For this reason, two case studies with different climatic conditions, as well as geological and thermal conditions have been included in this work. This will allow the analysis pursued to cover alternative cases and operating conditions of the GSHP and ASHP solutions. The two assumptions are located in the country of Spain, in a center region (Ávila) and in the Mediterranean coast (Alicante). The selection of these areas is based on the climatic differences of both scenarios and the variety of geological characteristics as explained in the following subsections. In both cases, a single-family house of 140 m^2 is considered for the corresponding calculations of each heating system.

It is important to mention that the evaluation of the heat pump systems will be carried out in the heating mode to optimize and adapt the calculations to the conditions of both locations, since in the region of Ávila, the installation of cooling systems is not frequent.

2.2.1. Geographical Location and Climate Conditions

As previously commented, both assumptions belong to the country of Spain. In the following Figure 3, it is possible to observe the location of the regions included in the study as well as the exact location of the areas that make up the case studies.

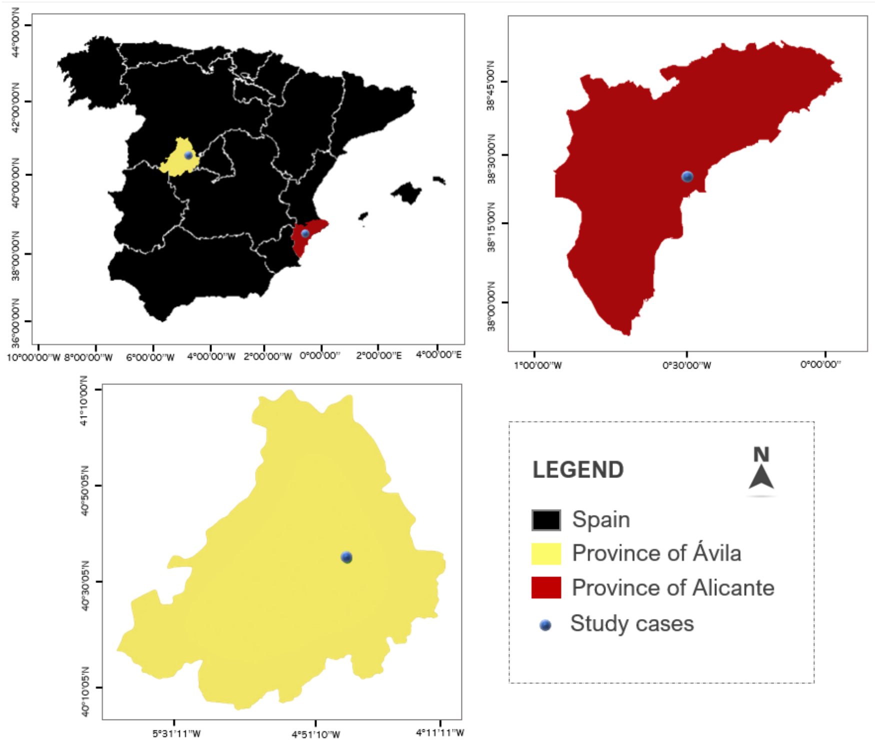

Figure 3. Location of the areas included in the present research. * Coordinates are expressed in latitude and longitude.

Regarding the climatic characteristics of each region, Ávila (from here on considered as Case 1) is associated with a slightly continental climate, with moderately cold winters and mild summers. On the other hand, the province of Alicante (Case 2) is on the southeastern coast of the country, with mild and relatively rainy winters and hot and sunny summers, typical of the Mediterranean climate. Table 2 presents the main climatic parameters associated with each of the regions for the year 2021.

Table 2. Climate conditions of the areas considered as study cases for the year 2021. Case 1: Ávila, Case 2: Alicante [35].

	Case 1	**Case 2**
Average annual temperature	11.9 °C	18.8 °C
Maximum average annual temperature	17.8 °C	23.7 °C
Minimum average annual temperature	6.6 °C	14.5 °C
Average annual humidity	62.4%	65%
Total annual precipitation	376.13 mm	319.29 mm
Average annual wind speed	8.9 km/h	7.5 km/h

2.2.2. Geological Characterization

In the case of the design of the low enthalpy geothermal system, it is essential to know the in-depth composition of the subsoil and with its characterization from the thermal point of view. For this, firstly, the following Figure 4 presents the main geological formations in each of the study areas taken from the official database of the Geological and Mining Institute of Spain.

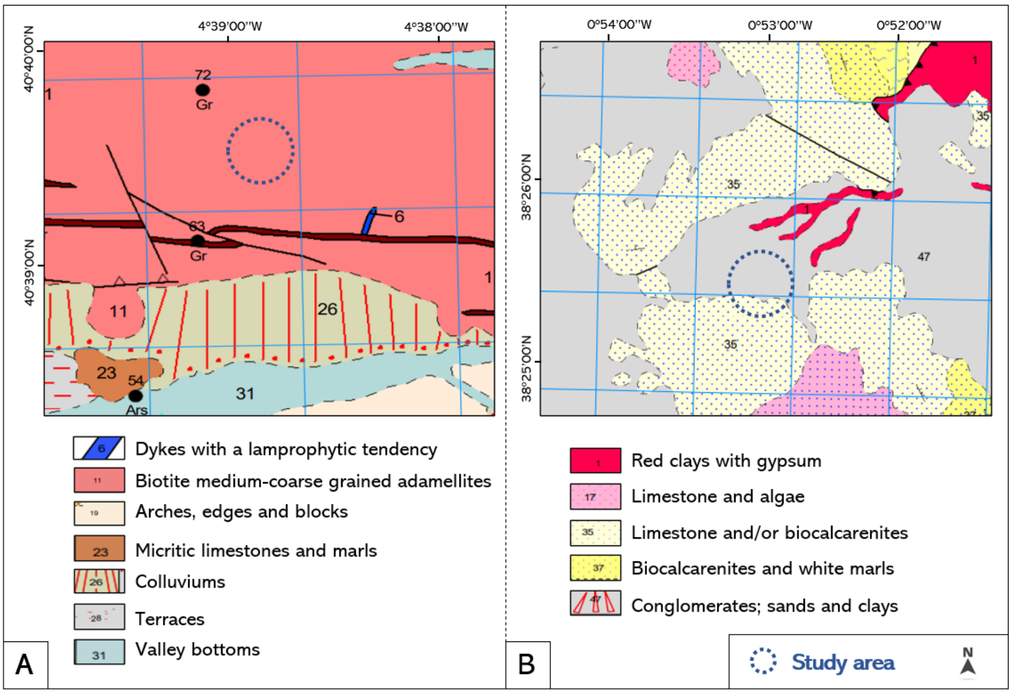

Figure 4. Geology of the areas considered in this research. (**A**) Case 1 (Ávila), (**B**) Case 2 (Alicante) [36].

Based on this first geological approximation (which just shows the materials found in the surface), and with the aim of delving into the in-depth composition of the ground, 2D Electrical Tomography surveys were performed in each of the study areas. This geophysical technique consists of measuring the apparent resistivity with a tetra-electrode device and with a constant separation between electrodes. Distances between the pairs of emitter–receiver electrodes are then varied by multiples of a value "n", in such a way that in the result it will be an apparent resistivity section at several levels "n" in depth. Data are finally treated by means of mathematical inversion algorithms [13].

In this work, SYSCAL Pro equipment was used for the electrical tomography surveys and Res2dinv software was implemented for the results inversion based on the least squares inversion technique with smoothed restriction. As shown in the following Figures 5 and 6, profiles of 23 m (for Case 1) and of 750 m (for Case 2) were made in each of the assumptions. It must be clarified that in the case of Ávila, the regular geological conditions allowed us to reach the base rock bed with a much shorter profile length than in Case 2, where the geological variations of the area demanded longer surveys to obtain the in-depth changes of materials.

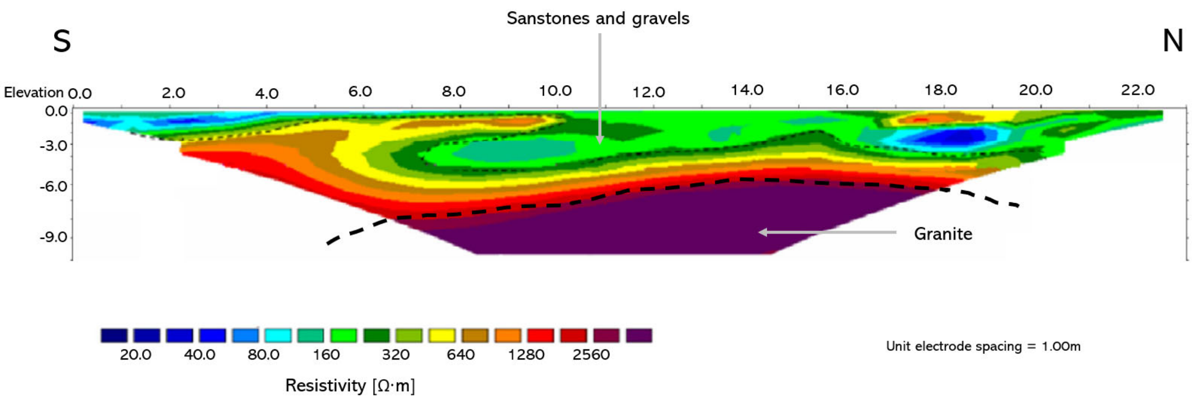

Figure 5. 2D electrical tomography profile for study Case 1, Ávila.

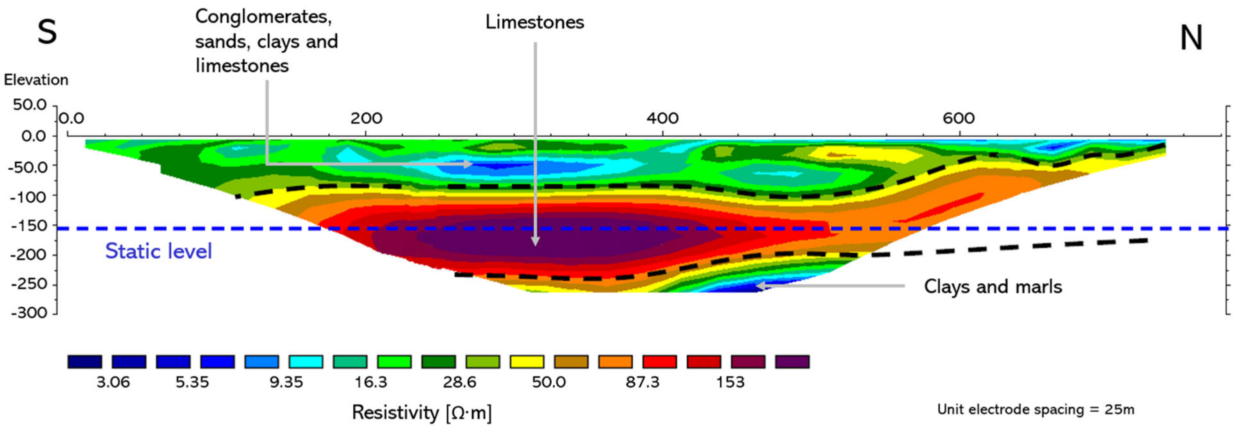

Figure 6. 2D electrical tomography profile for study Case 2, Alicante.

As can be seen in the previous profiles, the interpretation of each of the existing formations in each location has been added, based on the geological analysis and the electrical resistivity values obtained. Thus, the area of Case 1, located in the province of Ávila, stands out for being an eminent granite geological context. From approximately 6 m in depth, the bedrock would be reached, meaning that the geothermal design will necessarily have to be made considering that drillings will be in contact with this rock.

About Case 2, in Alicante, formations of conglomerates, sands and clay are located in the first levels. At a depth of 150 m a formation of consolidated limestones is found, although its influence on the geothermal drilling design would be practically null (common drillings are usually limited to 100–150 m).

3. Results

3.1. Energy Heating Demand

Before carrying out the corresponding dimensioning of the ground source and air source heat pump systems, it is necessary to define the energy needs for the base building in each of the selected locations. For this purpose, a specific tool that allows us to obtain the annual and monthly energy demand distribution has been implemented.

The program follows the monthly method prescribed in the standard regulation UNE-EN ISO 52016-1 [37] and enables us to analyze visually and intuitively the sensitivity of different variables on the energy behavior of the building, where only geometry is available. Specifically, the tool uses climate and energy databases for different locations and asks the user to enter data about the geometric characteristics and dimensions of the building and the layout of openings and windows. The following Table 3 includes the results of the mentioned calculations in each location. As commented before, only heating demand is considered for the analysis pursued in this research (since Case 1 does not require a cooling system). It must be mentioned that the building considered in this work is constituted by normal insulation materials and that in both scenarios the transmittance values provided by the tool have been considered.

Table 3. Heating and cooling energy demand for the building included in the study in each of the described locations.

	Case 1	Case 2
Heating energy needs (kWh/year)	32,207	14,306

3.2. Ground Source Heat Pump System

Once the energy demand of the building is estimated, this subsection details the calculation of the geothermal system to cover the required heating needs. In this sense, the geothermal design software GES-CAL [38], developed by researchers from the University of Salamanca, has been used. This program allows obtaining the configuration of the geothermal well field and the corresponding heat pump by introducing a series of parameters of the scenario: (i) the energy demand previously calculated, (ii) different characteristic parameters of the installation (type of heat exchanger and grouting material, COP of the heat pump), (iii) as well as the thermal conductivity of the subsoil in the vicinity of the installation. The tool is an effective and valid solution for the geothermal design of reduced heating energy demands (such as the ones here), that is capable of providing different heat exchanger configurations and schemas. However, its use is not recommended to calculate high-power geothermal systems, in which a more exhaustive evaluation of the ground and the heat carrier fluid behavior is required [39]. Performing a realistic evaluation, during the geothermal design of the software, the same characteristics of the geothermal system are used (32 mm polyethylene doble-U vertical heat exchangers, standard geothermal grout with thermal conductivity of 2.4 W/m K, geothermal fluid constituted by 30% glycol (monopropylene) and 70% water and heat pump with COP of 4) but modifying the heating energy demand and the geological context according to each study case. Considering the results of the geophysics surveys, the thermal conductivity associated with each geological formation has been estimated from previous authors' published research [40]. Results obtained with GES-CAL are shown in the following Table 4. Calculations consider that hot water is produced at the temperature of 45 °C and enters the heat pump with a seasonal range of 5–14 °C.

Table 4. Results obtained with GES-CAL software for the building under study in each assumption.

	Heating Demand (kWh/year)	Ground Thermal Conductivity (W/m K)	Heat Pump Power (kW)	Number of Boreholes	Total Drilling Length (m)
Case 1	32,207	3.0	5.76	1	98
Case 2	14,306	1.4	3.89	1	96

3.3. Air Source Heat Pump System

When selecting air source heat pump systems, whose use is directly conditioned by the collected external air, it is vital to consider the climatic conditions of the location in which the installation is expected to operate. As already seen in this research, the concept that refers to the level of energy efficiency of a heat pump and that is mandatory to use in the corresponding design of the system is the Coefficient of Performance (COP) in the case of the heating mode, and the Energy Efficiency Ratio (*EER*) for the cooling one. Expressions that defined the mentioned parameters are shown in the following Equations (1) and (2) [41].

$$\text{COP} = \frac{\text{Heat delivered to the space}}{\text{Electricity consumed}} \tag{1}$$

$$EER = \frac{\text{Heat extracted from the space}}{\text{Electricity consumed}} \tag{2}$$

However, given the particularities of the ASHP solution, when evaluating its performance in different locations, an additional concept must be introduced. This parameter, known as the Seasonal Performance Factor (*SPF*), refers to the seasonal net coefficient of performance in active mode for the case of electric heat pumps as the ones here considered (Equation (3)). *SPF* will be required for the correct selection of the heat pump device and to determine the real consumption of the equipment in the function of the characteristics of the region where it will be installed. In Spain, this factor must be greater than 2.5 so electric heat pumps can be considered within the group of renewable solutions [42].

$$SPF = \text{nominal COP}\cdot\text{FP}\cdot\text{FC} \tag{3}$$

where *FP* is a weighting factor that considers the different climatic zones of Spain and *FC* is a correction factor about the difference between the distribution temperature or use and the temperature for which the COP has been obtained in the test.

Table 5 presents the parameters that define each of the air source heat pump systems in each location, considering that Case 1 is included in climatic zone "E" and Case 2 in climatic zone "B" and a condensing temperature of 45 °C in both cases. Based on these values, Table 5 also includes the power of the air source heat pump required in each system from the energy demand associated with the building in each of the cases considered. Heat pump powers are calculated for an annual operation period of 2400 h (the usual period considered in this kind of calculation to face the system requirements in all the possible peaks of demand) and following the identical oversizing that GES-CAL software does in order to cover any unforeseen event not considered in the normal demand of the building.

Table 5. Design parameters for the air source heat pumps in each of the locations of the building for an initial COP of 4.5.

	FP	FC	*SPF*	Heat Pump Power (kW)
Case 1	0.64	0.77	2.21	8.47
Case 2	0.68	0.89	2.72	4.59

Beyond the initial calculation of the ASHP powers, it is necessary to determine the airflow that must be extracted by the external unit of each of the systems. In this context, the first step is to define the daily energy demand in the most unfavorable month (January) required in both scenarios. From these values and considering the initial COP of the heat pump (4.5) the energy that the external air (*Ea*) must provide in one day is obtained following Equation (4).

$$E_a = \frac{(\text{daily energy demand (January)})\cdot(\text{COP} - 1)}{\text{COP}} \quad (4)$$

Complementary to the air energy just calculated, it is also required to know (from official databases) the average minimum temperature and the average relative humidity of the air for the mentioned coldest month in each location [35]. All the information described up to this point can be seen in Table 6.

Table 6. External air energy required for the conditions of each study case.

	Daily Energy Demand-January (kWh)	Ea (kWh)	Minimum air Tª (°C)	Average Relative Humidity (%)
Case 1	161.30	125.5	−1	81
Case 2	98.09	76.29	8	69

The air entering the external unit at the defined minimum temperature frequently undergoes an additional temperature drop in the system heat exchanger (this work considers a common decrease of 2 °C for both scenarios). The enthalpy of the air must be then collected for both values, the minimum external air temperature (T1) and considering the temperature drop (T2) and for the relative humidity considered. The enthalpy difference obtained from the previous values establishes the energy available for each unit of mass of the outside air. Finally, considering the usual efficiency of the heat exchanger (80%) in this kind of system [43], the final values for each of the scenarios are obtained (Table 7).

From the above results and taking into account the air density for the minimum temperature of each case, it is possible to obtain the air energy per volume unit in kWh/m^3. Finally, as shown in Table 8, the air volume and the air flow rate are calculated from the enthalpy difference of Table 6 and the daily working period of the heat pump. This period is established by distributing the annual 2400 h of operation of the heat pump according to the seasonal needs of each month and day in each location.

Table 7. Available enthalpy of the external air in each scenario.

	Enthalpy for T1 (kJ/kg)	Enthalpy for T2 (kJ/kg)	Enthalpy Difference (kJ/kg)	Final Enthalpy Difference (kJ/kg)
Case 1	2023.28	2018.23	5.05	4.04
Case 2	1744.11	1739.50	4.61	3.69

Table 8. Air density, air energy, air volume and air flow rate required for each of ASHP systems.

	Air Density for T1 (kg/m^3)	Air Energy (kWh/m^3)	Air Volume (m^3)	Air Flow Rate (m^3/h)
Case 1	1.30	0.00146	85,958.90	7814.45
Case 2	1.25	0.00128	59,601.10	3725.07

Based on the previous results, the ASHP model requires operating with an external unit capable of providing an airflow like the one estimated in each scenario. This means that in Case 1 a heat pump with higher power than the foreseen in Table 5 must be selected. In this way, the commercial model required in Case 1 is a heat pump of 15 kW that provides an airflow rate of 8000 m^3/h and a 5 kW heat pump for Case 2 operating with an airflow rate of 3800 m^3/h [44].

4. Discussion

4.1. Heat Pump Energy Consumption

Before proceeding with the economic evaluation of both scenarios, an initial study of the heat pump use has been performed. Based on the results obtained in each of the heat pump systems in each location, the monthly distribution of the consumption of the pumps in the two study cases considered is shown below (Figure 7). This distribution is based on the need of hours of operation of the GSHP and ASHP systems according to the heating demand requirements in each zone.

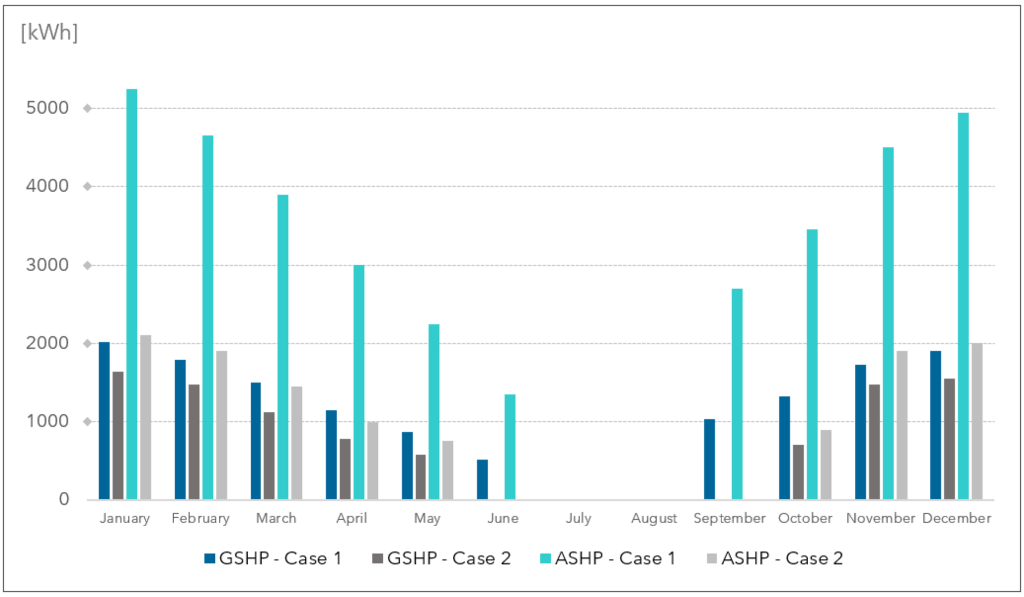

Figure 7. Monthly consumption of the different heat pumps alternatives in each Case.

As shown in the previous Figure 7, the consumption of ASHP alternative is higher in both cases, but especially in Case 1 (Ávila), where the more severe external air conditions reduce the *SPF* of this system and obliges to operate with a heat pump model capable of extracting the required flow rate of external air. In Case 2, the difference between both systems is not so evident because of the mild weather and geological context where is set.

4.2. Economic Analysis

Based on the analysis of energy consumption associated with each heat pump system, this subsection discusses the suitability of each of the alternatives considered from the economic point of view. With this aim, the first step is the estimation of the initial investment required in each solution and scenario. This information (included in Table 9) is automatically obtained for the geothermal installations from GES-CAL software, while for the ASHP systems, it has been estimated based on the standard commercial rates of the selected equipment.

Table 9. Initial investment associated with each study case in each of the heat pump systems evaluated in this research.

	GSHP	ASHP
Case 1	EUR 20,176	EUR 11,900
Case 2	EUR 18,942	EUR 8600

As can be easily seen from the previous Table 9, the initial investments are much higher in the geothermal systems, due in both cases to the drilling required as part of the well field.

From the above values of the mentioned Table 9 and considering the operating costs during the period of useful life considered (30 years), the final evaluation of each system is shown in the following Figure 8. For the realization of the graphs shown in this Figure 8, the cost of the electricity has been assumed as 0.25 EUR/kWh following the current trend of the electricity mix in Spain. In addition, and in order to take into account in this calculation the evolution of this cost, results are expressed in terms of Net Present Value (NPV) with a discount rate of 18%.

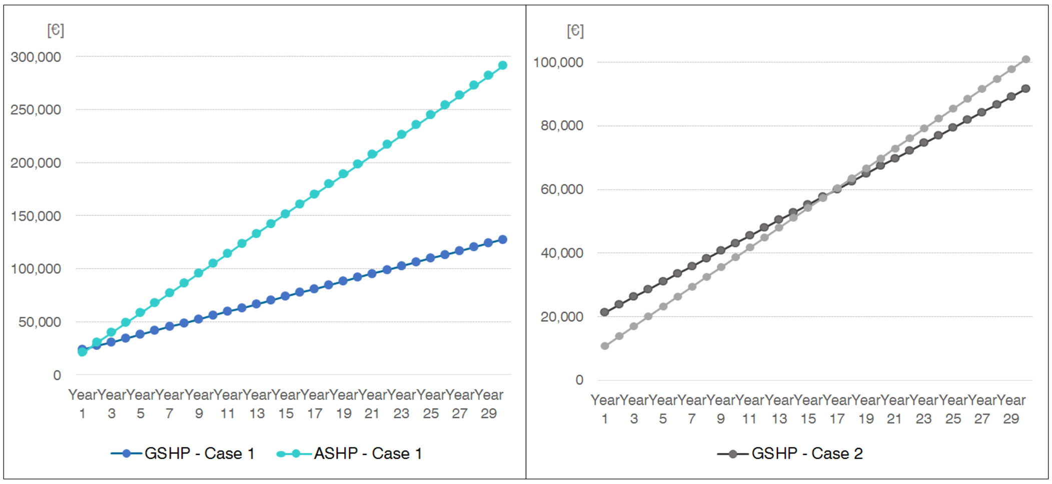

Figure 8. Economic comparison of the heating systems included here in both scenarios, Case 1 (**left**) and Case 2 (**right**).

Starting with the graph represented on the left of Figure 8, corresponding to Case 1, the conclusion is clear and evident. Despite the initial investment required in the geothermal system being practically double that of the ASHP solution, the great difference in the annual energy consumption of both heat pumps means that the amortization of the higher investment of the geothermal system occurs in just two years of operation. From that moment on and until the end of the 30 years considered in this evaluation, the savings obtained with the geothermal system are quite considerable, taking into account that the accumulated costs of the geothermal system in this period would be approximately EUR 130,000 compared to almost EUR 300,000 required in the aerothermal alternative.

Focusing now on Case 2 (graph on the right), the initial investment is, as in the previous case, much lower in the aerothermal system (due to the cost of drilling). Regarding the operating costs of the heat pump, the higher COP of the geothermal system makes the costs associated with this solution lower than in the ASHP, achieving an amortization of the initial investment of the geothermal system in the 17th year of operation. From this point, moderate savings would be achieved with this solution up to the year 30 evaluated. In this sense, it should be noted that the low difference between both systems in Case 2 is mainly due to two reasons: the ASHP system does not require such a high external air flow rate (due to the temperate climate of the area), and the geological context is not as favorable for geothermal use as in Case 1.

4.3. Environmental Impact

The differences in the energy consumption of the heat pumps of each studied system are directly manifested in the number of CO_2 emissions emitted into the atmosphere. Based on the electricity consumption of the heat pumps and considering the energy mix of Spain, the accumulated emissions during the entire useful life period for each scenario are shown in the following Figure 9.

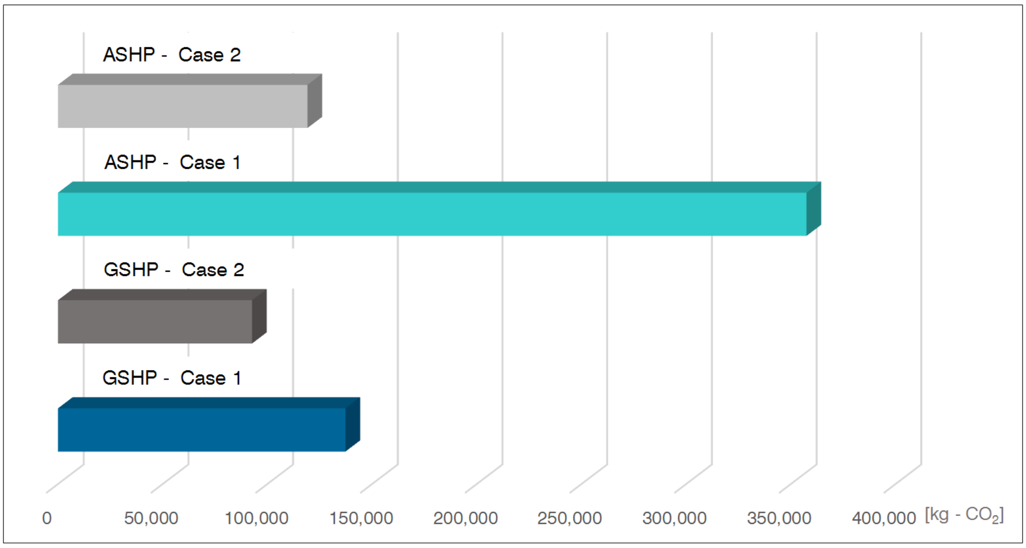

Figure 9. CO_2 emissions accumulated during the 30 years of useful life of each assumption. * Calculations are based on an emission factor of 0.331 kg CO_2/kWh electricity [45].

As presented in the previous Figure 9, the emissions associated with the use of the ASHP system in Case 1 are considerably higher at the end of the 30th year of operation. All of this is once again due to the high external unit requirements because of the severity of the climate in the area studied. In addition to this environmental issue, the visual impact of the aerothermal external equipment must be considered, which depending on the location, can be quite annoying when the needs for outdoor air, as in Case 1, are so demanding.

5. Conclusions

This research presents a comprehensive comparison of GSHP and ASHP solutions in two different scenarios. The evaluation carried out aims to provide new guidelines when selecting the most suitable renewable heating system based on the particularities of the location in which it is planned to be installed. For this reason, two completely opposite areas are included in the study: Case 1, a geologically favorable environment for thermal exchange but with high heating energy needs, and Case 2, where the temperate climate characteristics significantly reduce the heating energy requirements but not so ideal for the thermal exchange with the subsoil. Based on these conditions, the results obtained in this research lead to draw the following considerations:

- The dimensioning of a shallow geothermal system is strongly influenced by the geological conditions of the area. In this sense, it is considered essential to carry out initial studies (as geophysics) of the thermal and geological characterization of the formations in order to adjust the design to the conditions of the location.
- In the case of the ASHP systems, it is an essential requirement to consider not only the *SPF* of the installation but also the external air conditions of the area to ensure that the system is properly designed and will be capable of responding to the most severe conditions. If this factor had not been considered here, lower power heat pumps would have been selected with the consequent failures and incapacities of the system when facing unfavorable weather conditions.
- In the case of locations with cold climates, such as Case 1, it is important to exhaustively analyze the technical and economic feasibility of an aerothermal system. As this scenario shows, the geothermal system is much more economically and environmentally advantageous, together with the lack of need for outdoor units that can generate a certain visual impact. In this case, and given the favorable geological conditions, the balance clearly falls to the geothermal system in which the amortization occurs during the first years of operation, although in less suitable geologically areas, the geothermal system will be probably also the preferred choice.
- In Case 2, with a mild climate, both heat pump systems are quite similar from the economic and environmental points of view. The decision of one or the other system will depend on the user, who will have to analyze if the initial investment (greater in geothermal energy) is affordable and opt for achieving the savings associated throughout the useful life of the installation.

Author Contributions: Conceptualization, C.S.B. and I.M.N.; methodology, C.S.B. and I.M.N.; software, J.C.G. and P.C.G.; validation, A.F.M. and D.G.-A.; formal analysis, C.S.B. and I.M.N.; investigation, C.S.B. and I.M.N.; resources, J.C.G. and P.C.G.; data curation, J.C.G. and P.C.G.; writing—original draft preparation, C.S.B. and I.M.N.; writing—review and editing, C.S.B., A.F.M., D.G.-A. and I.M.N.; visualization, C.S.B. and I.M.N.; supervision, A.F.M. and D.G.-A.; project administration, C.S.B. All authors have read and agreed to the published version of the manuscript.

Funding: The work was co-financed by the European Regional Development Fund (ERDF), under the order of the Ministry of Education from Castilla y León. (Project ref.: SA102P20 in the framework of the main research "GEO-DISTRICT 3.0".

Data Availability Statement: Not applicable.

Acknowledgments: Authors would like to thank the Department of Cartographic and Terrain Engineering of the Higher Polytechnic School of Avila, University of Salamanca, for allowing us to use their facilities and their collaboration during the experimental phase of this research. The work was co-financed by the European Regional Development Fund (ERDF), under the order of the Ministry of Education from Castilla y León. (Project ref.: SA102P20 in the framework of the main research "GEO-DISTRICT 3.0".

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

References

1. Johansson, T.B.; Goldemberg, J. *Energy for Sustainable Development: A Policy Agenda*; U.S. Department of Energy: Washington, DC, USA, 2022.
2. Günther, M.; Hellmann, T. International environmental agreements for local and global pollution. *J. Environ. Econ. Manag.* **2017**, *81*, 38–58. [CrossRef]
3. van Vliet, M.T.H.; Yearsley, J.R.; Ludwig, F.; Vögele, S.; Lettenmaier, D.P.; Kabat, P. Vulnerability of US and European electricity supply to climate change. *Nat. Clim. Chang.* **2012**, *2*, 676–681. [CrossRef]

4. Lucon, O.; Ürge-Vorsatz, D.L. *Mitigation of Climate Change*; Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change in Buildings; IPCC: Geneva, Switzerland, 2013.
5. Kupiec, B. Legal status of a renewables self-consumer under Polish law in light of Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Stud. Pract. Prawnicze Adm. Ekon.* **2021**, *35*, 85–101. [CrossRef]
6. Paris Agreement. In *Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015: Paris)*; HeinOnline: New York, NY, USA, 2017; Volume 4.
7. Bouckaert, S.; Pales, A.F.; McGlade, C.; Remme, U.; Wanner, B.; Varro, L.; D'Ambrosio, D.; Spencer, T. *Net Zero by 2050: A Roadmap for the Global Energy Sector*; National Academies of Sceinces: Washington, DC, USA, 2021.
8. Hoogland, O.; Veenstra, E.; Vega, P.C.T.; Saastamoinen, H.; Kärki, J. *Study on Impacts of EU Actions Supporting the Development of Renewable Energy Technologies: Technology Sector Report, Bioenergy*; European Commission: Brussels, Belgium, 2019.
9. Broad, A. The EU Horizon Europe programme: Funding opportunities for the meteorological and climate community–basic and application areas (No. EMS2021-511). *EMS Annu. Meet. Abstr.* **2021**, *18*, ems2021-511.
10. Ramos-Escudero, A.; García-Cascales, M.S.; Cuevas, J.M.; Sanner, B.; Urchueguía, J.F. Spatial analysis of indicators affecting the exploitation of shallow geothermal energy at European scale. *Renew. Energy* **2021**, *167*, 266–281. [CrossRef]
11. Somogyi, V.; Sebestyén, V.; Nagy, G. Scientific achievements and regulation of shallow geothermal systems in six European countries—A review. *Renew. Sustain. Energy Rev.* **2017**, *68*, 934–952. [CrossRef]
12. Blázquez, C.S.; Borge-Diez, D.; Nieto, I.M.; Martín, A.F.; González-Aguilera, D. Technical optimization of the energy supply in geothermal heat pumps. *Geothermics* **2019**, *81*, 133–142. [CrossRef]
13. Nieto, I.M.; Martín, A.F.; Blázquez, C.S.; Aguilera, D.G.; García, P.C.; Vasco, E.F.; García, J.C. Use of 3D electrical resistivity tomography to improve the design of low enthalpy geothermal systems. *Geothermics* **2019**, *79*, 1–13. [CrossRef]
14. Blázquez, C.S.; Borge-Diez, D.; Nieto, I.M.; Martín, A.F.; González-Aguilera, D. Multi-parametric evaluation of electrical, biogas and natural gas geothermal source heat pumps. *Renew. Energy* **2020**, *163*, 1682–1691. [CrossRef]
15. Li, Z.; Luo, Z.; Wang, Y.; Fan, G.; Zhang, J. Suitability evaluation system for the shallow geothermal energy implementation in region by Entropy Weight Method and TOPSIS method. *Renew. Energy* **2022**, *184*, 564–576. [CrossRef]
16. EHPA. *European Heat Pump Market and Statistics Report 2015*; EHPA: Brussels, Belgium, 2018.
17. Miglioli, A.; Aste, N.; Del Pero, C.; Leonforte, F. Photovoltaic-thermal solar-assisted heat pump systems for building applications: Integration and design methods. *Energy Built Environ.* **2021**, *4*, 39–56. [CrossRef]
18. Blázquez, C.S.; Borge-Diez, D.; Nieto, I.M.; Martín, A.F.; González-Aguilera, D. Renewable energy integration as an alternative to the traditional ground-source heat pump system. In *Energy Services Fundamentals and Financing*; Academic Press: Cambridge, MA, USA, 2020; pp. 109–130. [CrossRef]
19. Shah, A.; Krarti, M.; Huang, J. Energy Performance Evaluation of Shallow Ground Source Heat Pumps for Residential Buildings. *Energies* **2022**, *15*, 1025. [CrossRef]
20. Soltani, M.; Kashkooli, F.M.; Dehghani-Sanij, A.; Kazemi, A.; Bordbar, N.; Farshchi, M.; Elmi, M.; Gharali, K.; Dusseault, M.B. A comprehensive study of geothermal heating and cooling systems. *Sustain. Cities Soc.* **2018**, *44*, 793–818. [CrossRef]
21. Blázquez, C.S.; García, P.C.; Nieto, I.M.; Maté-González, M.; Martín, A.F.; González-Aguilera, D. Characterizing Geological Heterogeneities for Geothermal Purposes through Combined Geophysical Prospecting Methods. *Remote Sens.* **2020**, *12*, 1948. [CrossRef]
22. Staffell, I.; Brett, D.; Brandon, N.; Hawkes, A. A review of domestic heat pumps. *Energy Environ. Sci.* **2012**, *5*, 9291–9306. [CrossRef]
23. Carroll, P.; Chesser, M.; Lyons, P. Air Source Heat Pumps field studies: A systematic literature review. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110275. [CrossRef]
24. Baglivo, C.; Bonuso, S.; Congedo, P.M. Performance Analysis of Air Cooled Heat Pump Coupled with Horizontal Air Ground Heat Exchanger in the Mediterranean Climate. *Energies* **2018**, *11*, 2704. [CrossRef]
25. Lim, T.; Baik, Y.-K.; Kim, D.D. Heating Performance Analysis of an Air-to-Water Heat Pump Using Underground Air for Greenhouse Farming. *Energies* **2020**, *13*, 3863. [CrossRef]
26. Wu, R. Energy efficiency technologies–air source heat pump vs. ground source heat pump. *J. Sustain. Dev.* **2009**, *2*, 14–23. [CrossRef]
27. Ołtarzewska, A.; Krawczyk, D.A. Simulation of the Use of Ground and Air Source Heat Pumps in Different Climatic Conditions on the Example of Selected Cities: Warsaw, Madrid, Riga, and Rome. *Energies* **2021**, *14*, 6701. [CrossRef]
28. Kim, H.; Nam, Y.; Bae, S.; Cho, S. Study on the Performance of Multiple Sources and Multiple Uses Heat Pump System in Three Different Cities. *Energies* **2020**, *13*, 5211. [CrossRef]
29. Safa, A.A.; Fung, A.S.; Kumar, R. Comparative thermal performances of a ground source heat pump and a variable capacity air source heat pump systems for sustainable houses. *Appl. Therm. Eng.* **2015**, *81*, 279–287. [CrossRef]
30. Schibuola, L.; Tambani, C. Environmental impact and energy performance of groundwater heat pumps in urban retrofit. *Energy Build.* **2022**, *261*, 111964. [CrossRef]
31. Yamaguchi, K.; Ihara, T.; Kikegawa, Y. Observational evaluation of outdoor cooling potential of air-source heat pump water heaters. *Theor. Appl. Clim.* **2021**, *145*, 1007–1025. [CrossRef]

32. Nikitin, A.; Deymi-Dashtebayaz, M.; Muraveinikov, S.; Nikitina, V.; Nazeri, R.; Farahnak, M. Comparative study of air source and ground source heat pumps in 10 coldest Russian cities based on energy-exergy-economic-environmental analysis. *J. Clean. Prod.* **2021**, *321*, 128979. [CrossRef]
33. Xu, Y.; Huang, Y.; Jiang, N.; Song, M.; Xie, X.; Xu, X. Experimental and theoretical study on an air-source heat pump water heater for northern China in cold winter: Effects of environment temperature and switch of operating modes. *Energy Build.* **2019**, *191*, 164–173. [CrossRef]
34. Lemmon, E.W.; Bell, I.H.; Huber, M.L.; McLinden, M.O. *NIST Standard Reference Database: REFPROP Reference Fluid Thermodynamic and Transport Properties (Version 10)*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2018.
35. AEMET, Agencia Estatal de Meteorología. *Arcimís "Archivo Climatológico y Meteorológico Institucional"*; AEMET: Madrid, Spain, 2022.
36. IGME, Instituto Geológico y Minero de España. *MAGNA 50—Geological Map of Spain at a Scale of 1:50,000*, 2nd ed.; IGME: Madrid, Spain, 2022.
37. *ISO 52016-1:2017*; Energy Performance of Buildings—Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads—Part 1: Calculation Procedures. Asociación Española de Normalización: Madrid, Spain, 2017.
38. Bláquez, C.S.; Nieto, I.M.; Mora, R.; Martín, A.F.; González-Aguilera, D. GES-CAL: A new computer program for the design of closed-loop geothermal energy systems. *Geothermics* **2020**, *87*, 101852. [CrossRef]
39. Sáez-Blázquez, C.; Martín-Nieto, I.; Farfán-Martín, A.; González-Aguilera, D. Evaluation of different methodologies for the design of the wellfield in shallow geothermal systems. *Rev. Fac. Ing. Univ. Antioq.* **2021**, *105*, 9–19. [CrossRef]
40. Blázquez, C.S.; Martín, A.F.; Nieto, I.M.; García, P.C.; Pérez, L.S.S.; Aguilera, D.G. Thermal conductivity map of the Avila region (Spain) based on thermal conductivity measurements of different rock and soil samples. *Geothermics* **2017**, *65*, 60–71. [CrossRef]
41. Valizade, L. Ground source heat pumps. *J. Clean Energy Technol.* **2013**, *1*, 216–219. [CrossRef]
42. Directiva 2009/28/CE del Parlamento Europeo y del Consejo, de 23 de Abril de 2009, Relativa al Fomento del uso de Energía Procedente de Fuentes Renovables y por la que se Modifican y se Derogan las Directivas 2001/77/CE y 2003/30/CE. 2022. Available online: https://www.boe.es/buscar/doc.php?id=DOUE-L-2009-81013 (accessed on 26 October 2022).
43. Jouhara, H.; Almahmoud, S.; Brough, D.; Guichet, V.; Delpech, B.; Chauhan, A.; Ahmad, L.; Serey, N. Experimental and theoretical investigation of the performance of an air to water multi-pass heat pipe-based heat exchanger. *Energy* **2020**, *219*, 119624. [CrossRef]
44. Saunier Duval. *Technical Catalog of Air Source Heat Pumps*; Saunier Duval: Zamudio, Spain, 2022.
45. Government of Spain. *Factores de Emisión: Registro de Huella de Carbono, Compensación y Proyectos de Absorción de Dioxido de Carbono*; OECC: Madrid, Spain, 2018.