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Review

A Review on Geothermal Renewable Energy Systems for Eco-Friendly Air-Conditioning

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Abstract: Nowadays, air conditioning consumes, on average, around one-fifth of the total power used in buildings globally. The present paper aims to provide the present status on the employment of Earth-to-Air Heat eXchangers (EAHX) to contain the consumption of energy and to reduce the effect on the environment in response to the Montreal and Kyoto protocols in a way to achieve cleaner energy production with a low Global Warming Potential (GWP) and a low ozone depletion potential (ODP). Different peculiarities and applications (direct or hybrid) are critically analyzed and reviewed. Specifically, in this paper, the different hybrid applications presented in the literature, where the Earth-to-Air Heat eXchangers are coupled to advanced systems, are reviewed. Finally, an IoT-based EAHX control system plan is reported and discussed to optimize energy efficiency and thermal comfort to suit operating conditions under different time zones.

Keywords: renewable energy; geothermal; Earth-to-Air Heat eXchangers; ground source heat pumps

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1. Introduction

Air conditioning is a crucial point to be considered in the building sector (both residential and commercial), both from energy savings and comfort-ensuring points of view. The conventional and most widely spread are HVAC systems (Heating, Ventilation, and Air Conditioning) based on vapor compression [1,2]. Even if they easily ensure the desired thermal comfort in the building environments, they negatively contribute to energy consumptions since HVACs are energy-intensive systems [3,4]. Furthermore, even if the Montreal Protocol [5] and subsequent amendments [6] have been prescribed to progressively phase out ozone depleting refrigerants, the currently employed fluids (HFC) are due to high global warming potential [7–9]. New alternative fluids for vapor compression systems are found on natural fluids or HydroFluoroOlefins (HFO) [10–13], which have problems with flammability and costs.

Approximately 20% of the electricity used in buildings globally today is used to cool spaces using air conditioning units and ceiling fans. In addition to increasing emissions, the growing demand for cooling systems has created a tremendous burden on the energy infrastructure of many nations. There is little question as to whether the requirement for space conditioning on a worldwide scale and the energy necessary to supply it will increase for several upcoming years in the absence of strong legislative initiatives. However, there is a high likelihood of swiftly altering the surge in conditioning energy consumption by implementing measures to increase system performance [14–16]. In developed countries, the building sector impacts 30% of global energy consumption [17], and internally to the building sector, the energy consumption deriving from the HVAC operation is 50% of the overall power consumption of the whole expense.

Moreover, from a more global perspective, considering all fields and possible applications, refrigeration, and air conditioning are accountable, based on projections from the International Institute of Refrigeration, for over 20% of the world's power usage, on average, in 2020. This amount changes significantly among the worldwide countries, based both on the level of change and local climatic circumstances: 14% of the overall electricity demand of the USA is to be attributed to air conditioning, whereas in Mumbai (India), it accounts for 40%. The High-Level Board on Climate Change guesses that, considering the expected climate changes, the residential sector expects to see its energy demand for HVAC systems operating more than 13 times from 2000 to 2050 and more than 30 times up to 2100 [18]. If, on the one hand, climate change causes an increase in energy demand for air conditioning, on the other hand, since most systems are based on vapor compression, this increase contributes to the environmental (global warming) and energy crisis in a vicious circle that is dangerous for our future.

Hence, there is an international concern about containing energy consumption, enhancing the productivity performance of buildings, and minimizing the effect on the environment and human health.

The breaking points of the aforementioned vicious circle are: (i) the development of high-impact strategies for energy savings; (ii) an increase in the energy efficiency of air conditioning and refrigeration systems; and (iii) wide employment of renewable energy sources. In fact, improvements in the performance of HVAC systems have become a top priority for green policies. This is demonstrated, for instance, by the manufacturing industry's increasingly stringent efficiency standards for these systems, the creation of building classification and energy conformity assessments, and the consistency of proactive maintenance procedures for those kinds of systems. In particular, as stated explicitly in the European Directive on Renewable Sources and created by the so-called "green building" criteria, the regulations addressing the use of energy in the building industry aim to promote the use of renewable sources.

The growing interest in discovering substitutes for vapor compression-based HVAC systems has pushed researchers to make efforts to develop solutions based on renewable energies. Renewable energy is energy produced from sources that are available in nature and that may be utilized right away or stored through accumulation technologies. The most prevalent renewable energy sources include geothermal heat-based energy, photovoltaic, wind, biomass, precipitation, tidal energy, and waves [19–22]. Perhaps one of them, solar heating/cooling systems, uses solar energy substantially to heat and cool water for home and industrial purposes [23]. Solar power is used to generate electricity using photovoltaic (pv) systems [24].

As a matter of fact, in the panorama of renewable energy sources, next to solar, geothermal, and wind are also sources due to the big potential for electricity generation. Geothermal energy definitely dominated the renewable energy market in terms of installed electricity power about 30 years ago.

In recent times, the potential of employing geothermal sources for electricity generation has been surpassed and dominated by solar and wind. The data reveal [25] that the surpass on geothermal energy by wind and solar has occurred both in terms of growth rate and installed capacity. This is due to the high cost in charge of geothermal systems as an initial investment that couples with a long payback time. Moreover, the construction time is long, and it is difficult to find available spaces. In some cases, another factor is social acceptance in geothermal power generation that could occur differently from country to country. To deepen these aspects, we suggest referring to the comprehensive and critical analysis provided by Li et al. [25] where the differences among worldwide countries in the use of geothermal have also been treated.

However, in addition to these considerations, geothermal is a largely available renewable energy source that is very suitable for air conditioning applications devoted to buildings [26]. The latter case is referenced to a direct use of geothermal energy: one of the most virtuous worldwide countries is Iceland, where until 2011, 66% of primary energy usage exploited geothermal; currently in Iceland, about 96% of the energy consumption coming from heating and cooling derives from this renewable energy source. Heat pumps are the systems that are best suited for the direct use of geothermal energy; however, on a global balance, the rest of Europe is not so virtuous since the International Energy Agency stated that only 3% of the energy consumption coming from building air conditioning is satisfied by geothermal systems.

A push toward developing efficient geothermal energy-based HVAC systems is more necessary than ever. Two main applications currently exist devoted to this purpose:

- Ground Source Heat Pumps (GSHP);
- Earth-to-Air Heat eXchangers (EAHX).

The present paper aims to provide a state-of-the-art study on the employment of these two applications for air conditioning of buildings. In the next sections, the main aspects related to them are discussed, analyzed, and reviewed.

2. Geothermal-Based Applications

2.1. Generalities

The exploitation of geothermal systems can enhance the energy efficiency of HVAC systems without disturbing indoor comfort settings. Geothermal systems have the potential to realize noteworthy outcomes of eco-sustainability and carbon footprint reduction [27]. A hybrid solar-geothermal conditioning unit is investigated to reduce the Global Warming Potential (GWP) according to the Paris Climate Change Agreement and Kigali Amendment, aiming to contain energy consumption and refrigerant use. The objective was to reduce the cooling energy requirements by 25–40% and reduce the refrigerant requirement by 25–30% [28]. Yang et al. [29] analyzed the cooling and heating energy consumption of a model of a plant factory in China using the simulation tool TRNSYS. The annual energy consumption of the plant factory (both for cooling and heating) was estimated, and the analysis revealed that geothermal-based systems, such as the GSHP designed and modeled in their investigation, are sufficient to supply the energy consumption of the farm and even to guarantee the optimal comfort conditions for cultivating vegetables inside them.

Fernández [30] potentially analyzed the reduction in terms of energy demand, environmental impact, and economic expense if geothermal energy were employed in supermarkets. With respect to the different weather conditions, three case studies were considered: a supermarket placed in Germany, Portugal, and Turkey. They concluded that the employment of renewable energy sources, such as geothermal, led to a reduction in consumptions of 45% in Germany, 30% in Portugal, and 36% in Turkey, respectively.

Cadelano et al. [27] deliberated the energy retrofit of a museum arranged in a historical building through the software TRNSYS. Specifically, the energy consumption and environmental impact were evaluated by investigating the energy performances before and after the introduction of GSHP as an HVAC system. They noticed that the energy consumption in the second case was reduced by 24%.

2.2. Earth to Air-Heat eXchangers (EAHX): Requirements, Design, and Recent Breakthrough Investigations

EAHX is an innovative and efficient passive technology that typically uses low-enthalpy geothermal systems, used in many countries to encourage and strengthen the usage of renewable energy sources and, at the same time, to contribute to the achievement of thermal comfort in buildings. The working fluid in EAHX is air. The EAHX system consists of one or more pipes buried at a depth of at least 1.5–2 m below the surface, i.e., where the soil temperature does not change during the year, known as the Earth Undisturbed Temperature (EUT) [31].

A well-designed EAHX system is utilized independently or in conjunction with a conventional HVAC system to suit the building's heating and cooling needs. The cheapest EAHX could be a pipe of the right size that is buried at the right depth and by which ambient air is blown. The pipe has an outlet that lets air into the inhabited space, and one end that serves as an air input [32]. In summer, hot air is cooled by the soil, which is at a lower temperature; subsequently, it is supplied to the environment to be air-conditioned. Dually, in winter, cold air is heated in the basement and supplied inside to guarantee satisfaction with the thermal comfort standard.

A plant with an EAHX system consists of three main components:

- Suction unit: The air essential for the process of the scheme comes from the suction of outdoor air. The suction unit must be sized according to the connected EAHX tube and the pressure loss that is achieved. Regarding the location of outdoor air intake, it is necessary to comply with the requirements of VDI 6022 [33]. The latter requires that the air intake be of excellent quality. When choosing the location of the air suction, the following points must be considered: the vicinity to the road (road traffic) and other buildings; the proximity to leaf-losing trees/shrubs; proximity to vent openings of any kind; and the main wind direction and location of any systems that can generate annoying odors. The suction towers for EAHX must be made of waterproof material and not pose any risk to health, while the height of the suction entrance must be at a sufficient distance from the earth's surface and from any pollutant emitters. The standard also requires that the suction tower be made of stainless steel.
- Filters: The use of filters in the suction unit can serve several functions. You can use a coarse mesh filter to protect EAHX from pollutant external agents. This is also possible with a medium or fine mesh filter. The use of the coarse mesh filter is suitable for normal operation and is sufficient to ensure compliance with standards and directives. The use of a fine mesh filter is preferable if special health protection measures are to be taken, e.g., in the case of allergies. It should be taken in mind that to increase the useful life of a fine mesh filter, a coarse mesh one is always inserted into it. For the complete system comprising an EAHX and a traditional HVAC system, the directives [33] provide for two levels of filtering, one in the intake unit and the other in the traditional ventilation system. Finally, it should be noted that with the use of a fine mesh filter, the pressure drop for the suction unit increases.
- Pipes: The pipes installed in the EAHX constitute the heart of the system, and it is through them that the transmission of heat amid air and soil takes place. For the material of these pipes, directive VDI 6022 provides for specific requirements: it must be closed cell, watertight, and resistant to corrosion; not harmful to health; the material from which it is made should not store moisture and is due to a system to drain the condensate that forms in the summer.

Hence, the key advantages and disadvantages in the employment of EAHX schemes are listed below.

Advantages:

- The employed fluid used is air (unlimited availability and free);
- Power consumption is lower when compared with the prevailing traditional systems;
- Higher coefficient of performance (COP) when coupled with traditional systems;
- The scheme is simple, so it entails less upkeep and functional costs;
- The eco-friendly EAHX exploits geothermal energy, a renewable energy source, and it does not require the use of refrigerants and compressors.

Disadvantages:

- The installation cost is high;
- The requirement of large available free areas to bury the pipes;
- Condensation may occur in the ducts, which must be removed with the help of small submersible pumps;

- The convective mechanism that is triggered in the tube does not allow it to reach uniform temperatures at the outlet of the exchanger;
- Because air is employed as a refrigerant, the presence of microorganisms could become the main cause of the need to couple the EAHX with a filtered ventilation system, with greater energy consumption and a decrease in air quality.

EAHX's could be used in a huge number of schemes, which vary from one another according to the scheme, the geometry of the exchanger, the quantity of pipes mounting the exchanger and how they are arranged, the material the pipes are made of, etc. The optimal and suitable scheme must consequently consider several vital parameters: technical considerations, such as the availability of material or free land surface; energy considerations, such as the size of the cooling/heating load of the building to be air-conditioned; and economic considerations.

EAHXs can be categorized using a wide range of factors. A suggested categorization of EAHXs is shown schematically in Figure 1 [33]. EAHX systems can be classified into open-loop and closed-loop EAHXs based on their architecture and design. While closed-loop EAHXs circulate air from a building until the appropriate temperature is reached, open-loop EAHXs pull air straight from the surroundings. EAHXs might replace traditional conditioners as a practical option while also providing a straightforward design, easing ecological consequences, and lowering expenses. When contrasted to a closed-loop system, which cycles the same air through the pipes, an open-loop system delivers clean, fresh air that rotates through pipes and fulfils building cooling and heating requirements [34].

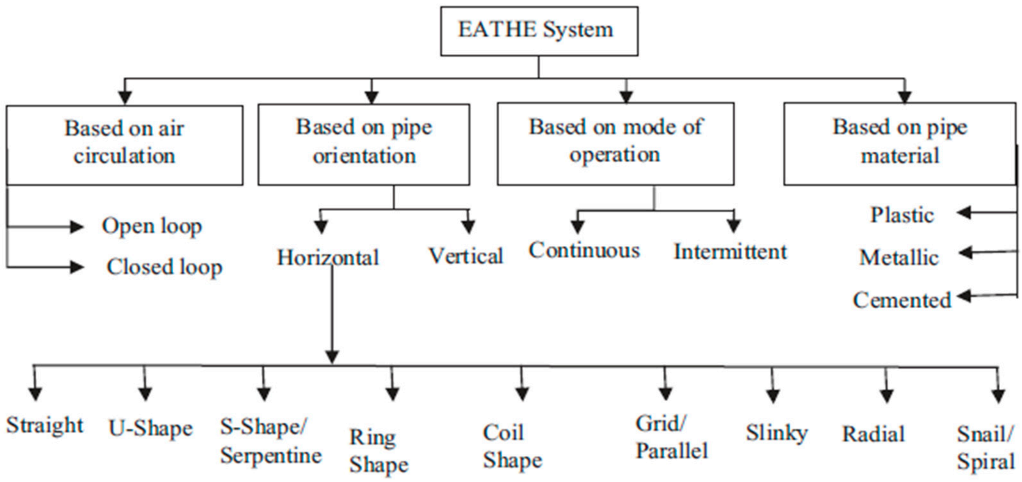

Figure 1. Classification of EAHX systems.

Because of their substantial influence on the lowering of heating/cooling energy loads and the enhancement of interior thermal comfort settings, EAHXs have proven to be appealing technological research. The cooling effectiveness of EAHXs has been researched under diverse geological and environmental circumstances, including relative humidity, air temperature, soil temperature, and air velocity. The EAHX was investigated to see if it might be used to improve energy performance within buildings while also lowering the electrical energy consumption of typical air-conditioning systems. Various upcoming and novel technologies will be useful in augmenting the performance of EAHX with suitable hybrid modes. Hybrid structures comprising hybrid nanofluids and microspray models and by incorporating wavy strips in the structures. These would enhance heat transfer efficiency and provide better thermal comfort as a final outcome [35–39].

2.3. Geometrical Parameters

Rodrigues et al. [40] carried out wide experimental procedures to evaluate the thermal and fluid-dynamic properties of a Y-shaped EAHX. The Energy Performance Indicator (EPI) was used to assess the EAHX's performance. The optimum configuration of the

Y-shaped EAHX boosted the value of EPI while also delivering monthly power savings, according to research [40]. The viability of a novel helical-shaped EAHX over conventional U–shaped EAHX is investigated for evaluating the thermal performances in a restricted ground space. outlet air temperature and effectiveness. The results indicated that the novel design offered an additional 80% of thermally comfortable indoor air conditions, even during peak summer. Similarly, the results also indicated that the novel design is efficient in heating operations to keep interior comfort in the winter spell [41].

Recent studies were also conducted on the impact of functional parameters, together with pipe length and pipe section (circular, rectangular, and elliptical), on the energy performances of EAHX, through sensitivity analysis. The outcomes indicated that the rectangular and elliptical buried pipes with larger surface area are more effective with >88% and >93% in contrast with the conventional (circular) one. The results also indicated that the efficacy of the length of the pipe is better over the pipe cross section [42].

2.4. Physics-Based Parameters

A pure buoyancy-driven EAHX system was recently explored for its practicality and cooling effectiveness by Long et al. [43] in 2022. This system combines solar chimney and thermal mass effects. The testing results revealed that the EAHX system could provide 24 h of varying natural ventilation and passive cooling, as well as significantly improve the indoor thermal environment under hot summer circumstances [43].

Recent studies have indicated that backfilling could augment the thermal potential of an EAHX beyond 400 m in depth to assist emergency ventilation. The backfilling system with low thermal conductivity proved to augment energy efficiency, thermal comfort, and thermal performance up to 100%, in contrast to the original system [44].

2.5. Integrated-Hybrid Systems

In 2022, an integrated passive system comprising a solar chimney with an EAHX (SCEAHX) was investigated by Long et al. [45] for its clean air and cooling capacity.

The SCEAHX system indicated 24 h of natural ventilation in conserving satisfactory indoor thermal comfort and temperature. A SCEAHX system based on Phase-Change Materials (PCM) was also studied to improve the interior thermal environment. The combined PCM-SCEAHX system, according to numerical analysis, not only increased usable cooling capacity but also produced more consistent interior thermal comfort conditions. As a result, the PCM-based SCEAHX system enhanced thermal inertia, regulated airflow rate during the day, and prolonged solar chimney's usage at night [45–47]. A recently developed water-aided EAHX was investigated for its energy efficiency with fins on the internal pipe of the double pipe heat exchanger. The results indicated that the overall heat transfer coefficients were enhanced, changing from 36–68% [48]. Researchers identified that hybrid building integrated photovoltaic/thermal (BIPV/T) and EAHX systems give greater yearly total electrical and thermal energies in contrast to the BIPV/T and EAHX systems. The hybrid system gives around 3% less yearly total thermal and electrical exergy and enviro-economic parameters in contrast with the BIPV/T. The exergo-economic factor of the thermal (BIPV/T) and EAHX systems was >50% of that for the BIPV/T system [49]. Recently, a novel hybrid system was designed comprising a coupled EAHX with a concentrical 2-pipes heat exchanger as a clean energy source. The air is cooled when exchanging heat in the concentrical 2-pipes heat exchanger, having an internal pipe with longitudinal fins filled with water and ice/mixture of ethylene glycol as a PCM. The outcomes indicated that the convective heat transfer coefficient is noteworthy in the hybrid system with an attractive cooling solution, even during peak periods [50]. Another hybrid semi-transparent photovoltaic thermal (SPVT) greenhouse system, together with an EAHX, has been developed to grow plants in a warm season. The impact of air variations, packing factor on photovoltaic (PV) cells, and mass flow rate of air flowing through EAHX, greenhouse gas, and plant temperatures is examined. Outcomes show that the hybrid SPVT-EAHX unit produces >125 kWh of daily inclusive sustainable exergy [51].

2.6. Climatic Conditions

For use in a desert climate, a numerical analysis of the thermal efficacy of an EAHX was built and presented by Maytorena and Hinojosa [52]. The results were confirmed by contrasting them with numerical and experimental data from previous works collected under comparable environmental circumstances. Investigations focused on determining the EAHX's suitable air velocity inlet, causing the optimal chillness in the room with the proper air inlet and output arrangement [52].

Over the years, EAHX technology has proven to be promising for space heating/cooling. In most regions, however, EAHX alone is insufficient to offer interior thermal comfort in all areas worldwide. However, a hybrid system combining an EAHX with an Air-Source Heat Pump (ASHP) has recently been explored to give interior thermal comfort while also conserving energy. The hybrid system reduced average energy consumption and enhanced the value of COP during the summer and winter months when compared to a standalone ASHP for certain ambient air temperatures and humidity ranges [53]. An inventive vertical solar chimney with fins and an EAHX has been examined as a summertime supplementary ventilation and air-conditioning device in a hot, arid environment. The height, diameter, number of fins, depth, length, and diameter of the pipes that make up the EAHX, among other geometric characteristics of the solar chimney, were explored. The research revealed that this system met the ventilation objectives of labs and residential buildings, and that it was able to save 85% usage at its highest potential [54].

2.7. Coupled System of EAHX Upstream of the AHU

D'Agostino et al. [55] estimated the energy efficacy of a peculiar geothermal energy system in which an EAHX is situated upstream of the Air-Handling Unit (AHU) of an office air conditioning unit in Naples (South Italy). Research outcomes indicated that, using the EAHX, the saving of the thermal energy of the coils in the AHU is >40%. Additionally, the efficiency of the EAHX value reached up to 90% with modifications in the tube length and diameter; this value may settle at around 40–50% for the entire year. Li et al. [56] analyzed an Air-to-Air Heat Recovery (AAHR) device and an EAHX (arranged in series) and evaluated the viability of the novel system in severe cold regions. Performance tests indicated that the novel system brings a significant ecological and economic benefit in contrast to the traditional solution. The EAHX significantly reduced greenhouse gas emissions by 17%, which is an indication of energy savings with payback periods of 2.1 and 2.4 years (return rate of 8%).

Kalbasi et al. [57] verified how, by combining an AAHR, EAHX, with an AHU, the cooling energy reduces to an average 33% and 11% reduction in the overall essential power. Research indicated that the coupled system of AHU and EAHX could bring down the total energy falls by an average of 38% with a 100 m long tube, and this value of reductions could even be reduced by 38–49% with the increased length of the tube. Ascione et al. [58] assessed the consequences of using an EAHX in an air-conditioning system on energy efficacy and ecological impact. The results showed that the pre-treating unit connected with the EAHX (pre-cooling in the summer and pre-heating in the winter) resulted in a 30% energy reduction in winter and an average saving rate of 41% in the summer, for a worldwide saving rate of 31% annually.

D'Agostino et al. [59] analyzed a coupled system of EAHX + AHU for the entire year at various locations identified according to the Koppen classification [60]. The results indicated a best outcome for Milan (Italy), with a cooling and heating capacity saving of 55% for a 100 m tube length, indicative of a huge energy savings. The lowest outcome was in Lampedusa (Italy) and Rio de Janeiro (Brazil), where the heating + cooling capacity reduction was possible up to 39% and 24%, respectively. Nevertheless, the best results could be attained for a 100-m tube length in Ottawa (Canada), where the heating + cooling capacity was reduced by 65% when using the EAHX. D'Agostino et al. [61] also investigated an HVAC system composed of EAHX + AHU. They demonstrated the overall energy saving in the city of Naples (Italy) in winter rises from 17% to 47% for the range of tube lengths, 20 m to 140 m. In addition, the power savings in Ottawa (Canada) reached an all-out of 52% for 140 m tube length.

2.8. Ground Source Heat Pump (GSHP) and EAHX

Shimada et al. [62] analyzed the high energy-saving potential GSHP to promote energy and GHG reductions. GSHP designed based experimental work on a pilot facility was conducted. The simulation results indicated an energy savings of 40% for a 3-year GSHP procedure for a small government building in Bangkok. Fernández [30] analysis indicates that the GSHP system of the Portuguese group could exhibit a 30% drop of energy spending and 30% lessening of carbon dioxide emissions in contrast to the conventional space conditioning system. Similarly, GSHP with vertical- and horizontal-type EAHX reduced electricity consumption by 30% and 18%, respectively, in contrast to an ASHP [63,64].

A Gas Injection EAHX (GI-EAHX) with an air conditioning system was analyzed for peak loads by Richter et al. [65]. Experimental results indicated that there was a reduction in the exit temperature of up to 2 °C and cooling power is increased by 26% compared with an equivalent conventional setup. They indicated that the usage of several GI-EAHX within a larger geothermal field could offer reliable peak load handling with a reduced size of a geothermal system with a good thermal capacity [66]. Several researchers optimized the diameter of the EAHX to augment the heat exchange rate up to 3.45%, and a rise of 18.7% was achieved by using ripped inner pipe walls instead of conventional smooth inner walls [67]. Specific details on these aspects were exhaustively summarized by Florides and Kalogirou [68].

Table 1 summarizes the main investigations in which significant energy savings were detected through the employment of geothermal systems. Different geothermal systems have been analyzed, from the simple EAHX configurations toward the GSHP and hybrid solutions.

Table 1. Energy savings through geothermal systems.

Author	Location	Method	Energy Reduction/Savings	CO_2/GHG Reduction
Cadelano et al. [27]	Technical Museum Nikola Tesla in Zagreb	GSHP	48–66%	24%
Fernández [30]	German super markets Portuguese	GSHP	45%/30%	28%/30%
D'Agostino et al. [55]	Office building in Naples (South Italy).	EAHX + AHU	40–50%	–
Li et al. [56]	Cold regions	EAHX + AAHR	8%	17%
Kalbasi et al. [57]		EAHX + AAHR + AHU	38–49%	–
Ascione et al. [58]	Mediterranean climate	EAHX + air conditioning	29–46%	–
D'Agostino et al. [59]	Milan Lampedusa Rio de Janeiro Ottawa	EAHX + AHU	55% 39% 24% 65%	–
D'Agostino et al. [61]	Naples Ottawa	EAHX + AHU	17.5–46% 52%	–
Shimada et al. [62]	Bangkok, Thailand	GSHP	40%	–
Richter et al. [65]	Hamburg University of Technology	GI-BHXs + air conditioning	26%	–

3. Materials Used in Earth-Air Heat Exchangers

The energy converted by the EAHXs depends on design parameters such as the pipe's material, diameter, and depth [69]. The performance of ground-coupled heat exchanger systems is based on air/liquid flow rate, length, material, depth, diameter of pipe, temperature difference, soil temperature, capacity of blower fan, and different layout of pipes [70]. Sakhri et al. [71] reviewed how many researchers have conducted studies on the performance of EAHXs during summer and winter and found the effects of external and internal parameters. The materials employed for building an EAHX are also crucial aspects to consider. In their reviews, Darius et al. [72] and Peretti et al. [73] also considered the influence of the thermal properties of the design materials on the energy performance provided by these geothermal systems. Specifically, pipes made of steel, aluminum, plastics, and copper tubes were reviewed by Peretti et al. [73]. The requirements for pipe materials are resistance coefficients, wall roughness, anti-corrosive, and structurally stable. The functions of the tubes are to transport air and exchange heat with the soil.

In their investigation, Bansal et al. [74] reported that pipe materials do not affect performance much due to their thickness; therefore, cheaper materials can be used in pipes. Lekhal et al. [75] analyzed the performance of EAHX using zinc and PVC. The comparative study was conducted under a warm-temperature climate in northern Algeria. The results show that pipe material affects EAHX performance when EAHX passes from heating to cooling mode. The air outlet temperature provided by zinc pipes is 7.5 °C higher than the outlet temperature provided by PVC. Sakhri et al. [76] used two types of pipe materials: PVC and steel. It was found that PVC is better than steel since PVC is cheap, light in weight, easy to assemble, and modification of shape is possible. Figure 2 shows the variety of materials used in the pipes of the EAHX systems.

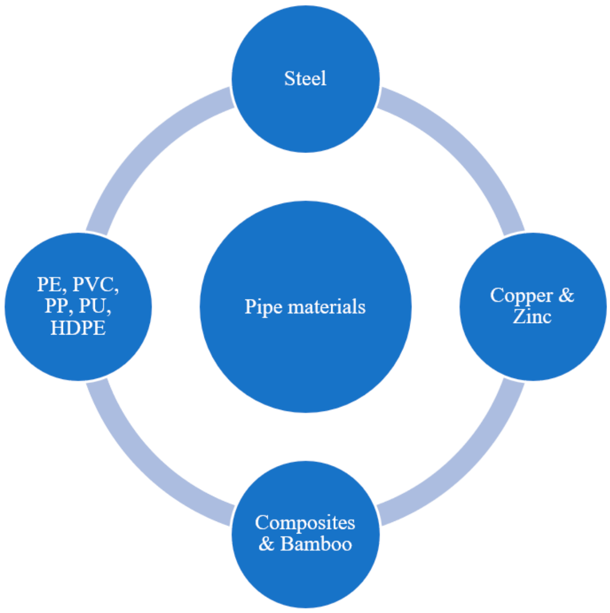

Figure 2. Variety of materials used in Pipes.

Bansal et al. [77] investigated the effects of pipe material and air velocity on the performance of EAHX systems. The investigations on steel and PVC pipes concluded that the velocity of air was found to greatly affect performance. The material having a high coefficient of friction affects the performance of the EAHX system. They concluded that convective heat transfer is dominant compared to conductive heat transfer. The effect of pipe materials on EAHX's performance was investigated. Zinc and PVC materials were used in the study. It was found that zinc EAHX exhibits higher efficiency in a climate with a COP of 9.5 compared to a steppe or arid climate having a COP of 8.2 or 8.1. PVC EAHXs are more suitable in the arid climate with a COP of 9.4 compared to the steppe climate with COPs belonging to the 7.6–8.4 range. The thermal performance of EAHX depends on the geo-climatic conditions and the pipe material [78].

Javadi et al. [79] reported that the most common material used in pipes of EAHXs is polyethylene (PE). Steel is most commonly used after PE. Copper and polyvinyl chloride (PVC) are also common. Polypropylene (PP), polyurethane (PU), composite, high-density polyethylene (HDPE), and polybutylene (PB) are rarely used. 60% of the GHEs use PE, 14% of the GHEs use steel, and 8% of the GHEs use PVC. Composite pipes exhibit better performance compared with the one provided by EAHXs made of HDPE pipes. The addition of aluminum wires to HDPE pipes increases the thermal conductivity. Steel pipes have greater heat transfer coefficients of pipe length than PE ducts.

Svec et al. [80] investigated the heat flow around an EAHX using plastic piping. It was found that the performance of the EAHX was affected when plastic piping was used.

An experimental investigation was performed in the north-eastern region of India [81]. Tunnel pipes were made of bamboo, and a cement–soil plaster mixture was employed to enhance the conductivity of bamboo pipes. Experiments were performed continuously for 7 days, and the delivered air temperature ranged from 25–26 °C with respect to the air temperature at the inlet, which ranged from 35 °C to 42 °C. The underground fresh air system is an easy and economically feasible technique. It reduces the consumption of energy, meets the power demand, and minimizes changes in climatic conditions in buildings.

4. IOT & Control Systems Used in EAHX

4.1. Control Systems Used in EAHX

The concept of EAHX provided by a control system is shown in Figure 3. As discussed in previous sections, EAHX is a green retrofit for cooling and heating buildings [82–84]. The concept of EAHX enables the insufflation of outdoor air directly into the building, providing more favorable conditions in reaching the required thermal comfort (less energy consumption to reach the indoor setting temperature) when coupled to an AHU or another existing air conditioning system [85,86]. Heat exchanges between earth and air increase with decreasing air velocity, altering the air flow rate in the duct and allowing for modification of its output temperature. Such a control would require measuring tools and a centralized control system on an actual structure. As shown in Figure 3, the main parts of the EAHX system IOT controlled are:

- Heat exchanger tubes;
- Sensors and actuators;
- Monitoring systems;
- Data acquisition system;
- Database server and control units;
- Filters, pump, and pump drives;
- Controllers.

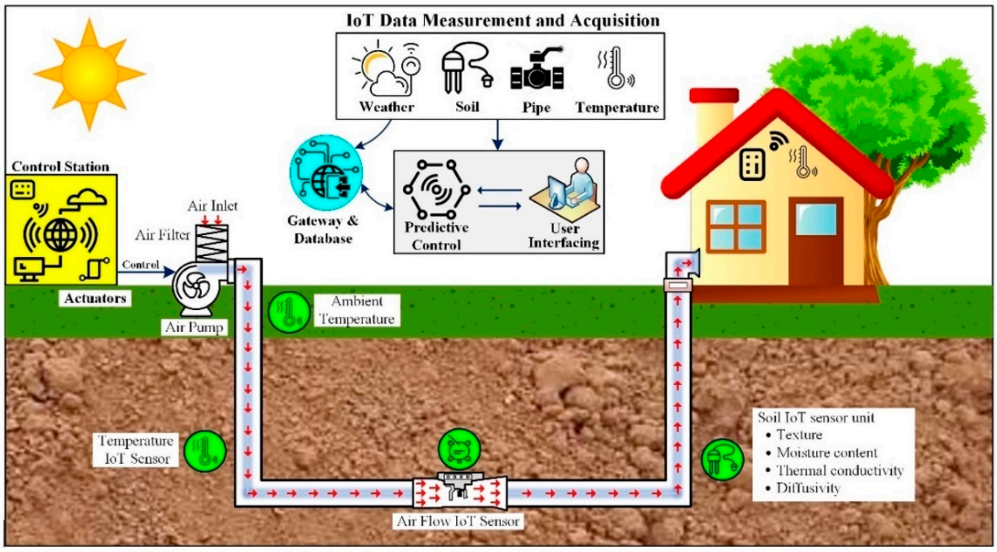

Figure 3. IoT-based control of the EAHX system.

The air pump has on/off control using a temperature sensor for ambient air and extracted room air, which can be set by the user. The aim of this on/off control strategy is to activate the EAHX air-handling unit. The recommended control set temperature for the EAHX air pump is based on user input and predictive control [87].

EAHX systems are designed to ensure hygrothermal effects in interior building environments, and their automated control can significantly improve end-users' comfort. Implementing novel control architectures and enabling the energy enhancement of EAHX systems without compromising building occupants' thermal comfort is of utmost importance. Combining two key modules—an intelligent control process and a smart physical infrastructure—can accomplish this. Energy enhancement and thermal comfort optimization must be the focus of the first module, while the sensing, communication, data storage, and actuation of the EAHX system in response to end-user demands are handled by the second.

The system continues to operate to keep the temperature within the building practically constant until the ideal temperature is reached. As a result, it discovers an air mass flow rate that uses less energy. Several methods have been developed throughout the decades for EAHX systems that may be taken into consideration in the control algorithm module. The majority are intuitive on/off controllers that are unable to account for significant thermal inertia EAHX processes. In addition, PID controllers with complex tuning for thermal inertia EAHX processes, whose performance may degrade during system dynamics. After reaching a steady-state temperature, the PID controller lowers the system's energy usage [88]. A PID controller may be used to decrease the variation in air fan power, which is a cubic function directly connected to the velocity of the air mass flow rate pumped into the building heat exchanger. Appropriate PID gain settings can further reduce this variation, as demonstrated in this study. This is so that the PID controller does not always have to operate at full capacity. When using a PID controller, the system uses less energy after the air inside the building reaches the desired temperature. This is because there is less energy being removed by the heat exchanger at this point because there is less of a difference between the desired temperature and the ground temperature. Furthermore, since fewer energy resources are required for cooling or heating a structure, PID control can improve both the EAHX 's efficiency as well as the sustainability of the globe.

The advantages of two cutting-edge heat exchanger control techniques, H control and µ-synthesis, are described in [89]. The necessity for a design process that explicitly tackles issues with modeling mistakes led to the development of H_∞ optimal control, frequency-domain optimization, and design theory. The H∞ control is developed further in the "µ-synthesis theory," where the uncertainty framework is considered while designing. A more effective predictive control strategy has gained traction over the past 20 years. This control method enables the efficient integration of energy efficacy methods into controller construction, together with problems such as disturbance rejection, constraint fulfillment, and slow-operating dynamic control [90]. Furthermore, the implementation of optimum regulating methods for the improvement of energy efficacy and thermal ease is becoming more abrupt and accessible as a result of the falling prices of smart devices. Advances in information and communication technology (ICT) enable the wide availability of dispersed sensors and data analytics tools. Therefore, it becomes clear that model predictive control is meaningless without being connected to a suitable smart infrastructure that enables the collection and transmission of actual data from the field [91]. By enabling the connecting of sensors, actuators, and other items to the internet and enabling both the awareness of the environment and interaction with it, the Internet of Things (IoT) extends a suitable solution.

4.2. IoT-Based Control of EAHX Systems

Due to the confluence of many technologies, things have changed. Digital intelligence is given to otherwise dumb gadgets by linking all these different things and giving them sensors, enabling them to communicate real-time data without a human being's input. The Internet of Things, which connects the real and digital worlds, is making the environment around us smarter and more responsive. Devices that can sense, analyze, and wirelessly transmit data to an unnamed storage place are used. such as the cloud, which stores, analyses, and presents data in a useful format, the IoT is expected to revolutionize our world by assisting us in monitoring and controlling basic development in our environment [91]. IoT frameworks facilitate communication among "things," with the majority of these frameworks appearing to focus on real-time data solutions. Big data and the Internet of Things are two developing technologies that may be used to generate information and enable applications for energy-efficient buildings [92]. Effective forecasting of heating and cooling demand is crucial to building energy management. One of the key uses of the IoT paradigm is the effective control of heating, ventilation, and air conditioning systems in smart buildings. The inside atmosphere of smart buildings may be improved for energy efficiency and thermal comfort using an IoT-based EAHX control system design [93]. The components are as follows:

It consists of the following elements:

- A gateway connects the nets of sensors and actuators to the Internet;
- An external application programming interface provides weather forecasts;
- An external database server gathers and forwards data from/to the field and from/to the control unit;
- A network of sensors senses environmental conditions and transmits measurements to a gateway;
- A network of actuators controls the pump and connects with the gateway;
- An IP device that serves as the end-user interface and is connected to the database server and host;
- A control unit that connects with the database server and houses the MPC algorithm;
- A dashboard for keeping track of the environment's condition and adjusting the control system mode.

The proposed architecture's mode of operation and information flow are as follows: The network of sensors is used to detect energy usage as well as the internal environmental conditions (temperature, CO_2 level, number of occupants, etc.). The measurements are then transferred in periodic bursts to the control unit, where the Predictive Control algorithm is implemented, and finally to the gateway, which connects to the database server. The control actions provided by this algorithm to the EAHX systems provide the optimal trade-off between energy consumption and comfort for the specified comfort limitations in the foreseeable future. The devices that actuate the EAHX modules get these control commands from the gateway. These control instructions are sent from the gateway to the devices that operate the EAHX modules. The EAHX modules adjust the room's temperature in accordance with the algorithm's predictions. The database server also keeps track of temperature and energy use readings. Through the dashboard on an IP device linked to the database server, these measures are shown to the end user. Users may interact with the control unit through the dashboard and choose the preferred temperature and control mode (i.e., either manual or automatic).

5. Conclusions

The surge in worldwide power consumption and CO_2 emissions is due to air conditioning and refrigeration, which has resulted in a massive increase in global warming and ozone depletion potential. The need for energy increased to achieve the required thermal comfort inside houses and business organizations. Renewable energy has to be utilized instead of conventional energy to reduce pollution in the environment. Alternative methods are being developed to achieve thermal comfort inside buildings. Many passive techniques replace conventional methods to reduce energy consumption. Natural resources supply energy when passive techniques are used.

EAHXs are discussed and critically analyzed as possible solutions for cleaner energy generation and low environmental impact. Specifically, the different hybrid applications presented in the literature, where the EAHXs are coupled to advanced systems, are reviewed.

When it comes to the design of an EAHX, the pipe diameter, length of pipe, and number of pipes are the leading parameters to be decided. As the length of the pipe increases, the pressure reduces, resulting in an increase in thermal performance. A long pipe of a small diameter buried at a large depth with less airflow velocity enhances the performance of EAHX. The temperature at certain depths is the same since the soil's thermal inertial property remains the same throughout the year. EAHX is effectively used to heat the air during the winter and cool the air in summer. The temperature of the Earth remains constant at a depth of 2 m throughout the year. This is called Earth's Undisturbed Temperature (EUT). The EUT is higher than air temperature during winter and lower than air temperature during summer.

EAHX utilizes geothermal energy, which is considered renewable energy and sustainable. Since EAHX does not use a refrigerant, there is no greenhouse gas emission. Soil density, soil properties, conductivity, diffusivity, water, and rock beds are the governing factors for selecting the site for EAHX.

In addition, various integrated hybrid systems are discussed to suit the climate conditions of arid, semi-arid, and congested areas. Hybrid systems indicated higher heat transfer coefficients, higher energy performance, and higher enviro-economic values compared to standalone EAHX systems. Phase change materials is a consolidated and viable resourced for this purpose. It is already employed in vapor compression [94] When compared to a standalone EAHX, a hybrid EAHX based on Phase-Change Materials and an Air-Source Heat Pump lowered average energy consumption and enhanced COP value roundly by 10–15%. At its maximum capacity, EAHX with a finned vertical solar chimney could increase energy savings by up to 60–80%. When EAHX is placed upstream of an air conditioning system's AHU, it may achieve improvements in terms of energy performance of up to 85%. In addition, greenhouse gas emissions were reduced by 17%, and worldwide electricity consumption was lowered by 33–43%. Furthermore, when compared to high-density PE pipes, composite pipes perform better. The heat exchange of HDPE pipes was improved using aluminum wire. Steel pipes, however, have a higher heat exchange/meter of pipe length than PE pipes. Finally, an IoT-based and predictive control algorithm-enabled EAHX system is proposed to optimize energy efficiency and regulate room temperature with thermal comfort. From our point of view, these systems are destined to gain more and more space as a renewable energy-based solution for the next future.

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Abbreviations

AAHR	Air-to-Air Heat Recovery
AHU	Air-Handling Unit
ASHP	Air-Source Heat Pump
BHX	Borehole Heat eXchangers
COP	Coefficient Of Performance
EAHX	Earth-to-Air Heat eXchangers
EPI	Energy Performance Indicator

EUT	Earth Undisturbed Temperature
GHG	Green House Gas
GI-BHX	Gas injection borehole heat exchanger
GSHP	Ground Source Heat Pumps
GWP	Global Warming Potential
HDPE	High-Density Polyethylene
HVAC	Heating, Ventilation and Air Conditioning
IoT	Internet of Things
PB	Polybutylene
PCM	Phase-Change Materials
PE	Polyethylene
PP	Polypropylene
PU	Polyurethane
PVC	polyvinyl chloride
SC	Solar chimney

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