

Review

A Review of Earth-Air Heat Exchangers: From Fundamental Principles to Hybrid Systems with Renewable Energy Integration

Hanna Koshlak 

Department of Sanitary Engineering, Kielce University of Technology, Aleja Tysiąclecia Państwa Polskiego, 7, 25-314 Kielce, Poland; hkoshlak@tu.kielce.pl

Abstract: Earth-Air Heat Exchangers (EAHEs) provide a compelling solution for improving building energy efficiency by harnessing the stable subterranean temperature to pre-treat ventilation air. This comprehensive review delves into the foundational principles of EAHE operation, meticulously examining heat and mass transfer phenomena at the ground-air interface. This study meticulously investigates the impact of key factors, including soil characteristics, climatic conditions, and crucial system design parameters, on overall system performance. Beyond independent applications, this review explores the integration of EAHEs with a diverse array of renewable energy technologies, such as air-source heat pumps, photovoltaic thermal (PVT) panels, wind turbines, fogging systems, water spray channels, solar chimneys, and photovoltaic systems. This exploration aims to clarify the potential of hybrid systems in achieving enhanced energy efficiency, minimizing environmental impact, and improving the overall robustness of the system.

Keywords: earth-air heat exchanger; renewable energy; sustainable building; HVAC systems



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1. Introduction

The escalating global energy crisis exacerbated by climate change has intensified the search for sustainable and energy-efficient building solutions. The building sector is a significant contributor to global energy consumption. As urbanization and population growth continue, the demand for energy in buildings is steadily increasing. Heating and cooling systems, in particular, play a pivotal role in energy consumption, accounting for a substantial portion of the total energy demand in buildings. Recent studies [1–4] have highlighted the escalating trend in global building energy consumption and the growing share of heating and cooling. Furthermore, according to the World Energy Outlook 2023 [5], global energy consumption in buildings has been steadily increasing over the past decade. In 2022, the sector consumed approximately 1% more energy than in the previous year, maintaining an average annual growth rate of just over 1%. Electricity has become the primary energy source for buildings, accounting for around 35% of the total energy use in 2022, up from 30% in 2010. This shift toward electricity is driven by the increasing electrification of heating and cooling systems, as well as the growing adoption of electric appliances. Despite the increasing use of renewable energy sources, fossil fuels continue to play a significant role in building energy consumption. In fact, the use of fossil fuels in buildings has increased at an average annual rate of 0.5% since 2010. This trend is concerning, as it contributes to greenhouse gas emissions and climate change.

Global energy consumption in buildings is a complex issue driven by several interconnected factors. Primarily, urbanization and population growth have led to a significant increase in the number of buildings, thus increasing the demand for energy services. For example, the largest increase was observed in regions with rapidly developing urbanization, such as Southeast Asia, India, and China, and in some African countries, such as Nigeria [6,7].

Furthermore, changing climate patterns have exacerbated the need for heating and cooling. More frequent and intense heatwaves have led to increased reliance on air conditioning systems, while colder winters have increased the demand for heating [8–11]. The impact of climate change is particularly pronounced in regions with extreme weather conditions, such as those experiencing prolonged heat waves or severe cold spells [12].

In addition, increasing living standards have contributed to an increase in energy consumption in buildings [4,13]. As people's expectations of indoor comfort rise, there is a growing demand for energy-intensive appliances, such as air conditioners, refrigerators, and electronic devices [14,15]. Moreover, the trend toward larger homes and more complex building designs further exacerbates energy consumption.

These factors have collectively led to a substantial increase in energy demand for building heating and cooling, particularly in developing countries where urbanization and economic growth are rapidly accelerating.

As the demand for energy continues to grow, there is an urgent need for innovative technologies that can reduce energy consumption and greenhouse gas emissions. As a result, there is a growing demand for innovative technologies that can reduce energy consumption and improve indoor environmental quality. Among the promising solutions, earth-air heat exchangers (EAHEs) have emerged as a viable option to improve the energy performance of buildings. Earth-air heat exchangers (EAHEs) have emerged as a promising technology for design and operation. Their roots can be traced back to ancient civilizations, who recognized the thermal properties of Earth and used them for various purposes [16]. However, the modern concept of the EAHE, as we know it today, began to take shape in the mid-20th century. Early research focused on understanding the fundamental principles of heat transfer between the ground and air. Pioneer studies have investigated the thermal properties of different types of soil, the impact of pipe configuration, and the optimal design parameters for EAHE systems. These early investigations laid the foundation for the development of practical applications of EAHE technology.

The number of articles devoted to the assessment of EAHE systems for buildings has been increasing in recent years, and several extensive review papers on the topic can be found in the literature [17–25], allowing us to conclude that interest in this subject is rising.

By taking advantage of the relatively constant temperature of the subsurface, EAHE systems offer a sustainable and efficient means of heating and cooling buildings. Earth-to-air heat exchangers (EAHEs) have found wide applications in various sectors of construction and industry. In the building sector, EAHE systems have found widespread application in residential and commercial properties. From single-family homes to large-scale commercial complexes, EAHEs contribute to improved thermal comfort and reduced energy consumption. Their applications are diverse and include space heating and cooling [26–29], ventilation [20–22], process cooling [30], and agricultural climate control [31]. By pre-heating or pre-cooling the incoming air, the EAHE reduces the load on conventional HVAC systems. In addition, they provide fresh filtered air, improving the indoor air quality. According to [32–34], the implementation of EAHE systems demonstrates significant potential as an effective passive cooling and heating technology, particularly for lightweight buildings located in high-altitude cold regions. Their research findings indicate a substantial improvement in indoor air quality, attributed to increased ventilation rates and reduced

pollutant concentrations. Numerous studies have shown the effectiveness of EAHE in reducing energy consumption, improving indoor comfort, and reducing greenhouse gas emissions [35–39].

Recent studies have demonstrated the feasibility of integrating EAHE with solar energy, geothermal energy, and air heat pumps [40–45]. For instance, [46–51] investigated the performance of a hybrid system combining an EAHE, achieving significant energy savings compared with conventional HVAC systems. These types of solutions have the potential to increase the efficiency of energy buildings and reduce CO₂ emissions.

To optimize the performance of EAHE systems, researchers have conducted numerous studies to investigate the impact of these variables [52–57]. Additionally, advancements in modeling and simulation tools have enabled more accurate predictions of the performance of EAHE systems, thereby facilitating their design and optimization.

As technology continues to advance, EAHE systems have become increasingly sophisticated and efficient. Innovative design approaches, such as the use of advanced materials and intelligent control systems, further enhance the performance of these systems. Additionally, ongoing research is focused on optimizing the integration of EAHE with other building systems, such as HVAC and ventilation systems, to achieve optimal energy performance [51].

Despite the promising potential of earth-air heat exchangers (EAHEs), several significant challenges hinder their widespread adoption. These include substantial initial capital expenditure, sensitivity of system performance to variations in soil conditions, and the potential for gradual system degradation over time. To overcome these obstacles and maximize the long-term viability of EAHE technology, future research efforts should focus on developing innovative strategies to mitigate these challenges and enhance the long-term performance and reliability of EAHE systems.

Although numerous studies have investigated the performance and applications of EAHE systems, a comprehensive review that integrates the latest advances in the field is needed. This review provides a comprehensive overview of EAHE technologies, focusing on their applications in improving the energy efficiency and sustainability of buildings. By synthesizing the latest research findings, the significant potential of EAHE as a sustainable and energy-efficient solution for building air conditioning is demonstrated. This review will analyze different EAHE system configurations, including their integration with other renewable energy technologies, such as air-source heat pumps, photovoltaic systems, and solar chimneys. The analysis will assess the performance, environmental impact, and economic viability of these integrated systems. Finally, the review will identify key challenges and opportunities for future research and development, contributing to the development of sustainable building practices and informing the design and implementation of more energy-efficient and environmentally friendly building solutions. This review will cover the following key areas:

- the basic principles of heat transfer in EAHE;
- different configurations of EAHE systems, including open- and closed-loop systems;
- integration of EAHE systems with other building systems and renewable energy sources;
- challenges and future research directions.

By addressing these key areas, this review will contribute to the development of sustainable building technologies and support the move toward more energy-efficient buildings.

2. Materials and Methods

This study employed a comprehensive literature review approach to explore state-of-the-art EAHE technology. The primary sources of information included peer-reviewed articles indexed in reputable databases such as Scopus, Google Scholar, and Web of Science. Relevant keywords such as “earth-air heat exchanger”, “ground-source heat pump”, “renewable energy”, and “energy efficiency” were used to identify a large pool of potential studies.

A rigorous filtering process was applied to select the most relevant and up-to-date research articles [57]. Criteria such as publication date, research methodology, and alignment with the study objectives were considered. This process resulted in the selection of 16,324 scientific papers that formed the foundation of this review.

To gain deeper insight into the trends and patterns within the field of EAHE research, a bibliographic analysis was conducted. This analysis involved mapping the citation network, identifying influential authors and institutions, and analyzing the most frequently cited keywords [58].

The selected articles were then subjected to a thorough qualitative analysis to extract key findings, identify research gaps, and discern emerging trends in EAHE technology. This analysis enabled a comprehensive understanding of the current state-of-the-art and future directions in this field.

3. EAHE Fundamentals

3.1. Classification of EAHE Systems

Earth-air heat exchangers represent an innovative solution in the field of energy efficiency. By leveraging the relatively stable temperature of the subsurface, EAHE systems pre-condition outdoor air before it enters a building.

Earth-air heat exchangers (EAHEs) have evolved significantly over the years, with advances in materials, design, and control strategies. This classification scheme provides a framework for understanding the various types of EAHE systems that have emerged (Figure 1).

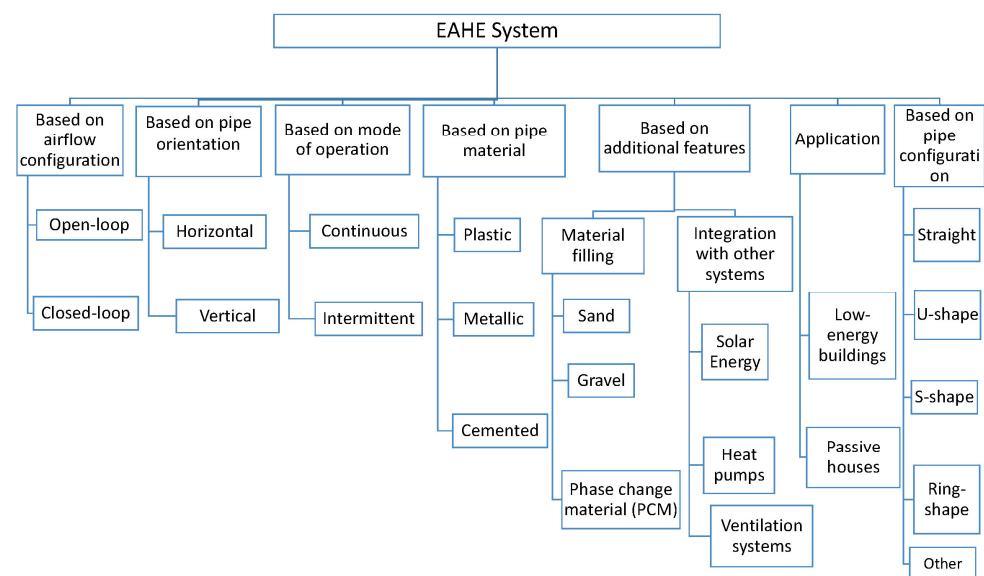


Figure 1. Classification of EAHE systems [24,35,59–82].

For different classifications, it is possible to appreciate the diversity of approaches to harnessing the thermal energy of the ground and to identify emerging trends in EAHE technology. Many researchers choose a hybrid configuration by coupling it with different

passive techniques to improve the performance of the system in their respective research work using experimental, analytical, numerical, or some other studies [59].

The fundamental principle of the operation of EAHE is based on the conductive heat transfer between the air flowing through underground pipes and the surrounding soil. Below a certain depth, the ground temperature exhibits relative stability year-round. Consequently, the energy requirement for conditioning ventilation air can be substantially reduced by leveraging low-grade natural energy reserves. As illustrated in Figure 2, ambient air is forced into the pipe, where it undergoes heat exchange with the adjacent soil and is subsequently delivered to the indoor environment for ventilation purposes.

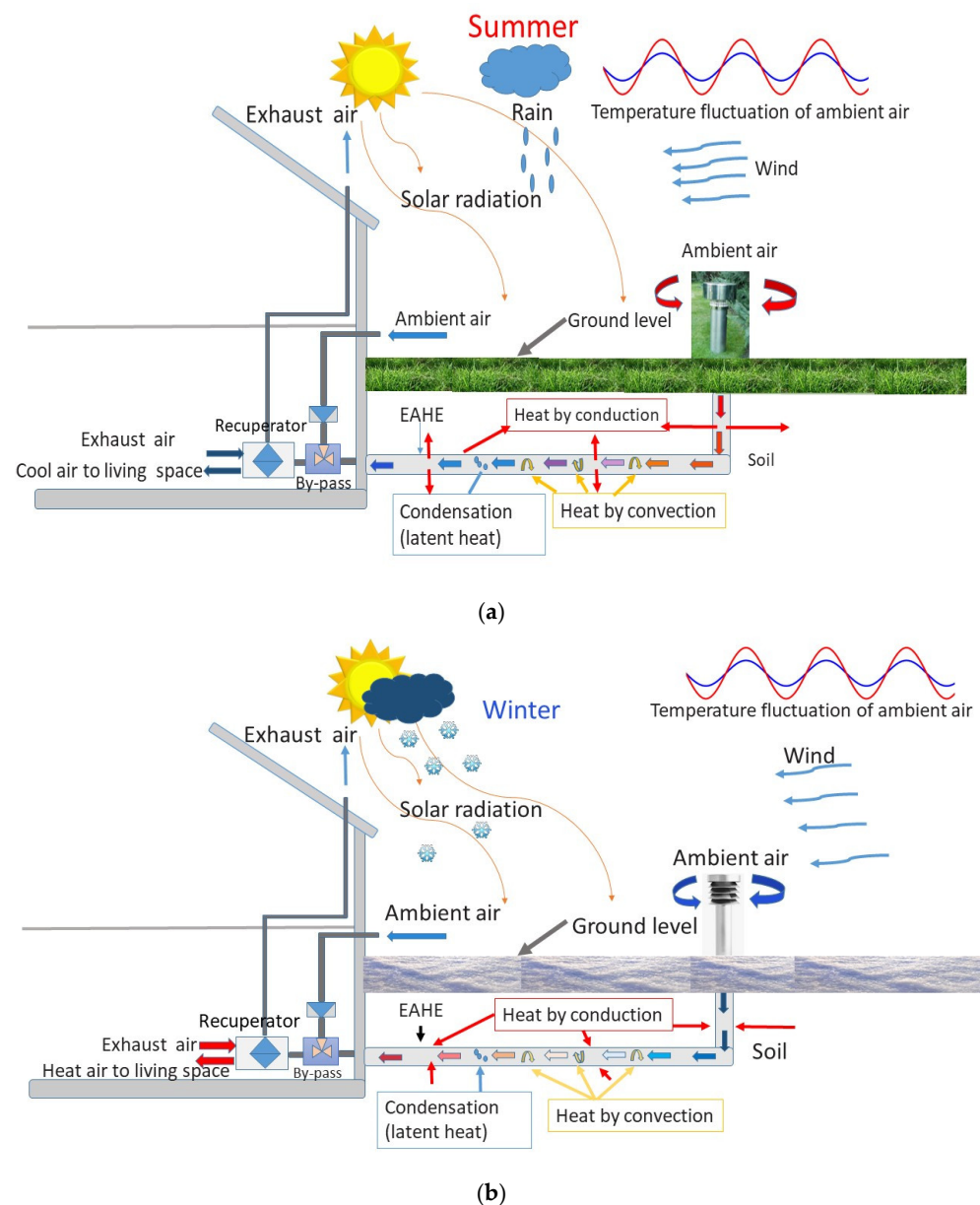


Figure 2. Working Principle of earth-air heat exchangers (EAHE) coupled with heat recovery units: (a) in summer; (b) in winter [83,84].

During summer (Figure 2a), warm ventilation air dissipates heat to the surrounding soil and undergoes a pre-cooling process before entering the indoor space. Conversely, in winter (Figure 2b), cool ventilation air can absorb heat from the surrounding soil, resulting in pre-heating. Although the ground temperature remains relatively stable throughout the year, seasonal variations occur, particularly in transitional seasons such as spring

and autumn. These fluctuations influence the effectiveness of heat exchange and require consideration during system design and operation. During these transitional periods, the EAHE system provides moderate cooling or heating depending on the prevailing outdoor temperature. Horizontal EAHE systems, characterized by pipes laid horizontally in trenches, offer certain advantages. They are generally easier to install in areas with shallow groundwater levels and may require less excavation. However, their thermal performance can be influenced by variations in soil temperature and moisture content, which can fluctuate more significantly near the surface [85].

Vertical systems are often preferred for urban or built-up areas where land is limited and for applications requiring higher heat transfer rates [86]. They involve drilling boreholes into the ground and circulating air through a buried pipe network [87]. Vertical Ground-to-Air Heat Exchangers (VEAHEs) offer several key advantages over their horizontal counterparts by accessing deeper ground temperatures [88]. With increasing depth, ground temperatures exhibit reduced sensitivity to external environmental factors, thereby minimizing the impact of surface temperature variations caused by diurnal and seasonal changes. This results in more stable and reliable heat transfer to the VEAHE throughout the year, improving the overall system performance [87,89,90]. However, vertical EAHE systems present some challenges (Table 1).

Table 1. The key differences between vertical and horizontal earth-air heat exchangers.

Feature	Vertical EAHEs	Horizontal EAHEs
Ground access	deeper ground temperatures	near-surface ground temperatures
Temperature fluctuations	less susceptible to near-surface temperature variations (diurnal and seasonal)	more susceptible to near-surface temperature variations (diurnal and seasonal)
Impact of weather	less affected by weather conditions (e.g., solar radiation, precipitation, soil moisture)	more significantly affected by weather conditions
Installation	typically requires more complex and potentially more expensive installation	generally easier and less expensive to install
Land use	requires less land area	requires more land area
Maintenance	may be more challenging to access and maintain	generally easier to access and maintain

As shown in Table 1, drilling boreholes typically incur higher installation costs compared to trenching for horizontal systems, which can significantly increase the initial investment. Furthermore, borehole stability can be a concern in certain geological conditions, requiring careful site investigation and appropriate installation techniques to mitigate the risks of borehole collapse. Additionally, vertical systems may not be feasible in areas with high groundwater levels, limited space for borehole installation, or regions with high seismic activity. In conclusion, both horizontal and vertical EAHE systems offer viable solutions for improving energy efficiency. The optimal choice depends on a variety of factors, including site-specific conditions, project budget, desired thermal performance, and environmental considerations. A thorough site assessment and comprehensive cost-benefit analysis are crucial for selecting the most suitable EAHGE system for a given application.

3.2. Heat and Mass Transfer in Earth-Air Heat Exchangers

A thorough understanding of the heat and mass transfer processes within earth-air heat exchangers (EAHEs) is paramount for the design and optimization of these systems.

Heat and mass transfer within earth-air heat exchangers (EAHEs) involves complex interactions between buried pipes, surrounding soil, and supply air (Figure 3).

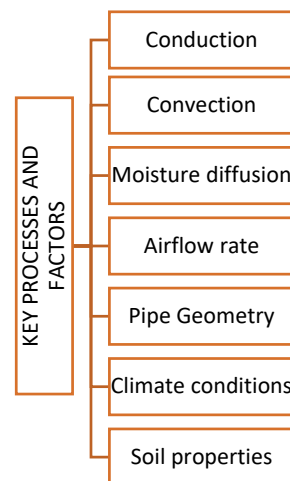


Figure 3. Key mechanisms and parameters affecting heat and mass transfer in EAHEs.

The interactions between the heat exchanger, soil, and supply air involve two areas of heat and mass transfer: the outer and inner surfaces of the heat exchanger pipe (Figure 4).

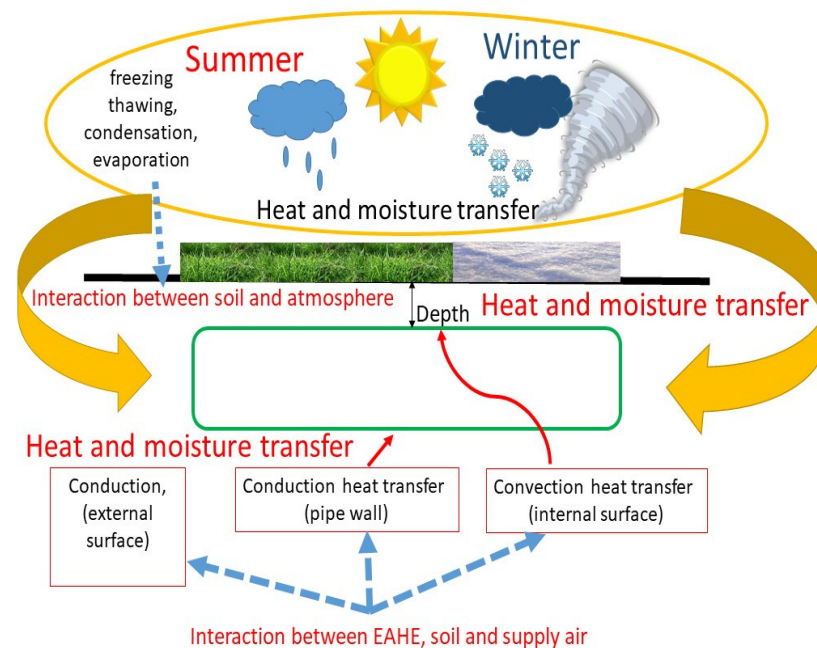


Figure 4. Heat and mass transfer in the EAHE.

At the outer surface of the buried pipe, heat is conducted from the wall of the pipe to the surrounding soil and governed by Fourier's law of heat conduction [91,92]. The rate of heat transfer is influenced by the thermal conductivity of the soil, its moisture content [93,94], and the temperature gradient between the pipe and the undisturbed soil. Additionally, moisture can diffuse between the soil and pipe wall depending on the relative humidity and temperature gradients. At the inner surface, heat is transferred convectively between the wall of the flowing air and the pipe [95]. The rate of convective heat transfer is influenced by factors such as air velocity, temperature difference between air and the pipe wall, and fluid properties. Moisture transfer is driven by concentration gradients and is influenced by relative humidity and temperature. Mass transfer, primarily in the form of moisture diffusion, can also occur between the air and the wall of the pipe, affecting the humidity of the supply air. The performance of earth-air heat exchangers (EAHEs) is influenced by a complex interplay of climatic factors, including temperature, precipitation,

and surface conditions. Seasonal variations in temperature and precipitation directly affect the thermal properties of the subsurface and, consequently, the heating and cooling capacities of EAHEs. The interaction between the atmosphere and the subsurface, as well as the specific characteristics of the ground surface, can further modify these effects. For example, vegetation cover can reduce surface temperatures through evapotranspiration, while frozen ground can reduce thermal conductivity. Understanding these interactions is crucial for optimizing the design and operation of EAHE systems in various climatic regions.

Accurate modeling of heat and mass transfer in earth-air heat exchangers is essential for their effective design and optimization [96]. While significant progress has been made in this area, challenges remain due to the complex interplay of factors such as soil heterogeneity, moisture migration, and variable boundary conditions.

3.3. Factors Influencing for Performance of Earth-Air Heat Exchangers

The performance of earth-air heat exchangers (EAHE) is contingent upon the capacity of the surrounding soil to store and release thermal energy. A multitude of factors influence the ability to serve as a thermal energy reservoir. These factors can be broadly categorized into soil properties, environmental factors, ground temperature profiles, and system design parameters (Figure 5).

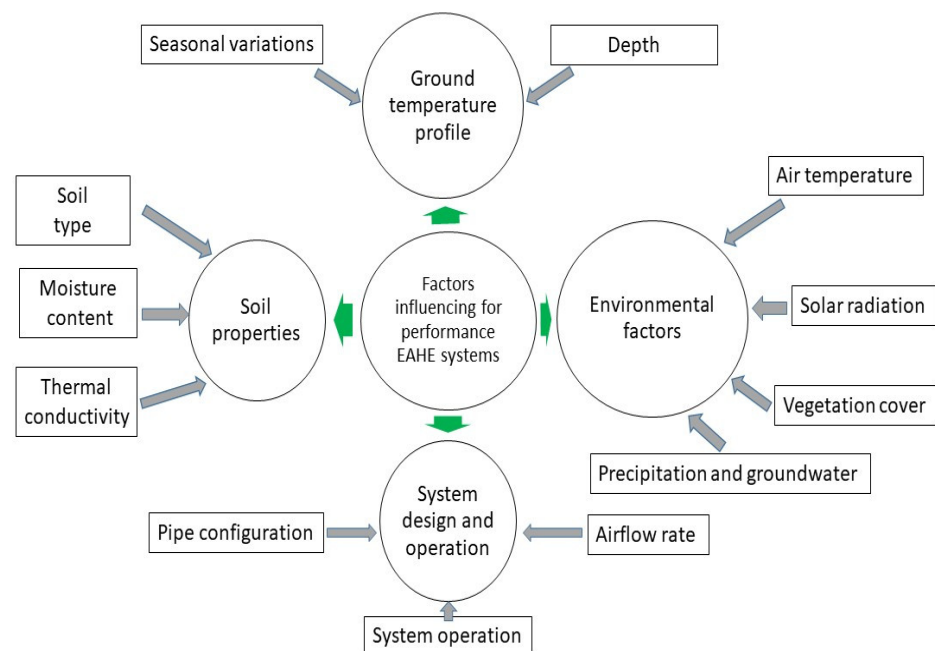


Figure 5. Factors influencing ground energy storage for EAHE system operations [97].

3.3.1. Effect of Soil Properties on EAHE Performance

Soil properties significantly influence heat transfer within the ground. The type of soil, such as clay, sand, or loam, plays a crucial role in determining its thermal properties. Clay soils, with their high clay content, typically exhibit higher thermal conductivity compared to sandy soils. Recently, articles have drawn attention to such issues, showing how soils with higher thermal conductivity, such as clay-rich soils, generally exhibit better heat transfer compared to sandy soils [71,72,98]. However, the specific properties of each soil type can vary significantly depending on factors such as particle size distribution, porosity, and mineral composition. Moisture content significantly influences the thermal conductivity. The presence of water within the soil matrix generally enhances heat transfer due to water's high thermal conductivity [99,100]. However, excessive moisture can have detrimental effects. A high moisture content can lead to increased soil density, which

can hinder heat transfer. Moreover, it can contribute to the corrosion of buried pipes, compromising longevity and efficiency [101].

3.3.2. Effect of Burial Depth on EAHE Performance

Earth-air heat exchangers take advantage of the relatively stable ground temperature to provide heating and cooling. However, the temperature of the ground exhibits significant variations depending on the depth [102,103]. Determining the optimal burial depth for EAHE systems is crucial for maximizing system performance while minimizing installation costs. Numerous studies [20,104,105] have observed a distinct temperature gradient, with temperatures decreasing as the depth increases. This phenomenon creates a “zone of constant temperature” at a specific depth, usually ranging from 5 to 15 m [106]. This zone offers a stable thermal reservoir for EAHE systems, as temperatures remain relatively constant throughout the year. While deeper burial generally leads to more stable ground temperatures, studies have shown that the marginal increase in performance diminishes beyond a certain depth. Kaushal [107] observed that depths greater than 3.5 m offer minimal incremental performance gains compared to 3.5 m. However, the optimal burial depth varies depending on the location and site-specific factors. For example, ref. [108] found an optimal depth of 1 m in Malaysia, while Babar et al. [109] reported 3.96 m as suitable for Sahiwal, Pakistan, and Khan et al. [110] suggested 4.5 m for Lahore, Pakistan. These variations can be attributed to differences in soil properties, climatic conditions, and local ground temperature profiles. Ideally, the burial depth should be sufficient to reach a zone of relatively stable temperature while minimizing excavation costs. Therefore, the optimal burial depth should be determined based on a cost-benefit analysis, considering factors such as soil properties, ground temperature variations, and construction costs.

3.3.3. Effect of Climatic Conditions on EAHE Performance

The performance of earth-air heat exchangers is strongly influenced by climatic conditions. The ground temperature exhibits pronounced seasonal variations, with higher temperatures during summer and lower temperatures during winter. These fluctuations are primarily driven by changes in solar radiation and air temperature. During the heating season, when the ground temperature is higher than the desired indoor temperature, heat is extracted from the ground, while during the cooling season, excess heat is rejected to the ground. The magnitude of these heat fluxes is influenced by the temperature difference between the heat carrier fluid and the surrounding ground. Studies have shown that seasonal variations in temperature and precipitation significantly impact the heating and cooling potential of these systems. In [51,94,111], the performance of EAHE systems beneath grass and concrete surfaces was compared under different climates. Their findings demonstrated that vegetation cover, through evapotranspiration, can lead to lower subsurface temperatures and improved cooling performance compared to bare soil or concrete surfaces. Warmer climates typically offer greater heating potential, while colder climates provide better cooling performance. Additionally, the specific characteristics of the local climate, such as the annual temperature range and the frequency of extreme weather events, can influence the effectiveness of EAHEs. In addition to climatic factors, the nature of the ground surface also plays a crucial role. Studies have shown that different surface conditions, such as vegetation cover and soil type, can affect the thermal properties of the subsurface and, consequently, the performance of EAHEs [112]. The interaction between the ground surface and atmospheric temperatures, as emphasized by [113,114], exhibits significant seasonal variability due to changes in thermal properties and energy partitioning. For example, studies in various climatic zones have shown that different characteristics of the ground surface can significantly influence the performance of EAHE.

However, these studies have focused on warmer climates. In colder climates, seasonal variations in ground surface conditions, such as snow cover, soil freezing and thawing, and changes in soil moisture due to snowmelt, can significantly impact subsurface temperatures and, consequently, the performance of EAHE systems.

In cold climates, seasonal changes in ground surface conditions, such as freezing and thawing, can significantly impact EAHE performance. The formation of a frozen layer can reduce the thermal conductivity and alter the heat transfer mechanisms in the subsurface [115]. Moreover, snow cover can act as an insulating layer, affecting the heat exchange between the ground and the atmosphere. A study by Zajch et al. [116] demonstrated that in regions with distinct seasons, factors such as snow cover, soil moisture, and freeze-thaw cycles can significantly impact subsurface temperatures, directly affecting the performance of earth-air heat exchangers (EAHEs). Moreover, recent numerical models developed by Zajch et al. [117] provide more accurate predictions of the impacts of climate change scenarios on ground temperature and EAHE efficiency. Despite these advances, more research is needed to fully understand the effects of extreme weather events and changes in land use on EAHE performance.

3.3.4. The Influence of Design Parameters on the Performance of Earth-Air Heat Exchangers

The performance of earth-air heat exchangers (EAHEs) is significantly influenced by various design parameters, including pipe material, dimensions, spacing, soil type, burial depth, and airflow rate. These parameters must be carefully selected to ensure optimal heat exchange and energy efficiency. Recent years have witnessed a surge in research dedicated to optimizing the energy efficiency and design of earth-air heat exchangers (EAHEs). Modeling has proven to be an invaluable tool for predicting the influence of operational parameters, such as pipe length, radius, burial depth, and airflow rate, on the thermal performance of earth-air heat exchangers (EAHEs). While various computational tools are available for modeling EAHE systems, such as EnergyPlus (Version 8.7.0) and TRNSYS (version 17.0), these analytical tools are often cumbersome for rapid design iterations. Computational Fluid Dynamics (CFD) has emerged as a popular choice for researchers, offering a versatile platform for simulating EAHE performance. CFD's ability to discretize the system into a fine mesh and solve governing equations numerically enables rapid and cost-effective analysis. Numerous studies have highlighted the central role of geometric parameters, such as pipe diameter, depth, and length, in influencing system performance [118–125]. For instance, Haitham Sghiouri et al. [126] proposed a multi-objective optimization framework to design efficient and cost-effective earth-air heat exchanger (EAHE) systems. Their framework was validated through an experimental exchanger model, key design parameters were identified, and a genetic algorithm was employed for optimization. The optimization aimed to minimize the life-cycle cost (LCC) while maximizing the cooling potential across three diverse Moroccan climates. Multi-criteria decision-making methods were then applied to determine the optimal configurations for each location. The results emphasized the importance of site-specific design, as optimal configurations varied depending on factors such as the ground temperature gradient. For example, the optimal design for Marrakesh and Oujda was a 160 mm diameter, 49 m long pipe buried at 3 m depth, while Errachidia required a similar pipe buried at 4 m due to its higher ground temperature gradient. The EAHE systems delivered cooling potentials of 1447 kWh/year, 1172 kWh/year, and 1739 kWh/year with corresponding LCCs of \$4122, \$4091, and \$4073 over 50 years for Marrakesh, Oujda, and Errachidia, respectively. The normalized life-cycle cost (NLCC) was lowest for Errachidia (\$0.234/kWh), followed by Marrakesh (\$0.285/kWh) and Oujda (\$0.349/kWh).

Despite advancements in earth-air heat exchanger (EAHE) technology, the impact of channel cross-sectional geometry on the thermal performance and indoor air quality of earth-air heat exchangers (EAHE) has been a relatively understudied area [127]. Recent studies have indicated that the thermal performance of EAHEs is directly correlated with the heat transfer surface area within the channels. Wei et al. [128] investigated rectangular channels in straight EAHEs, finding that this configuration enhanced heating and cooling performance, providing more stable channel wall temperatures and reduced soil thermal disturbances compared to circular channel configurations. Jahanbin [129] examined elliptical channels in vertical U-shaped EAHE and observed a 17% improvement in reducing the system's thermal resistance compared to circular U-shaped channels. Benhammou et al. [130] conducted a case study on EAHEs for cooling applications, demonstrating that rectangular and elliptical channels outperformed conventional circular channels. Specifically, rectangular and elliptical channels provided approximately 88% and 93% more heat transfer surface area between the air and soil, respectively.

Numerous studies have investigated the influence of the airflow rate on the thermal performance of earth-air heat exchangers (EAHEs). Although higher airflow rates can improve heat transfer, they can also reduce system efficiency due to shorter contact times between the air and the ground [131]. The optimal airflow rate is a complex interplay of factors such as soil properties, climate conditions, and system design. While these parameters interact in complex ways, the specific relationship can vary depending on the soil conditions, climate, and system design. Benrachi et al. [132] provided insights into this complexity by showing that increasing wind speed from 2 m/s to 2.5 m/s resulted in a substantial decrease in cooling effectivity, from 60% to 33%. Moreover, ref. [112] explored the impact of airflow velocity on heat transfer rates, demonstrating that a decrease in velocity and an increase in diameter result in a reduced pressure drop along the length of the pipe during the airflow. However, Mihalakou et al. [133] observed a decrease in the temperature difference between the inlet and outlet air with increasing pipe diameter at a constant airflow rate. In conclusion, a review of the literature revealed that while airflow velocity and pipe diameter play an important role in determining EAHE performance, the performance of EAHE optimal design parameters depends on a complex interaction of factors, including soil properties, climate conditions, and system configuration.

Multi-pipe EAHEs have emerged as a promising technology for enhancing building energy efficiency. While offering advantages such as reduced pressure losses compared to single-pipe systems [134], multi-pipe EAHEs present design challenges, particularly regarding uneven airflow distribution among individual pipes.

Numerous studies have investigated the impact of different configurations on EAHE performance [135–138] and have demonstrated that U-shaped configurations generally exhibit superior thermal performance compared to Z-shaped designs. These findings were corroborated by Qi et al. [139], who also observed improved thermal performance and airflow uniformity in L- and U-shaped configurations.

Despite these advantages, achieving optimal performance in multi-pipe EAHEs remains a challenge. Recent studies [140] have revealed significant disparities in airflow distribution among individual pipes, leading to suboptimal performance and potential inefficiencies. This uneven flow distribution can result in substantial variations in airflow rates between different branches [141], and the static pressure differential between the inlet and outlet of the final pipes can significantly affect the airflow.

Although U-shaped configurations have shown promise in mitigating these airflow disparities, neither U-shaped nor Z-shaped designs have limitations. Experimental and CFD studies [142] have demonstrated that U-shaped structures generally exhibit higher thermal efficiency due to a more uniform airflow distribution and reduced pressure losses.

However, CFD simulations [143] have indicated that U-shaped configurations can exhibit lower outlet temperatures, potentially impacting the overall system performance. This finding contradicts the results [144], which, using a simplified CFD simulation of a 5-branch EAHE, observed lower outlet temperatures for Z-shaped configurations. Furthermore, Z-shaped configurations exhibit greater variability in airflow distribution among parallel branches compared to U-shaped configurations of similar complexity. The total pressure drop is higher for 90-degree connections compared to 45-degree connections, leading to an increased overall pressure drop in the Z-shaped configurations. An uneven airflow distribution can have significant consequences, with [141] reporting potential thermal efficiency losses of up to 20% in multitube EAHEs. In conclusion, while multi-pipe EAHEs offer significant potential for improving building energy efficiency, their performance is highly dependent on the design and operating conditions. Future research should focus on developing more accurate models for predicting the performance of these systems, exploring innovative design solutions to address the challenges associated with uneven airflow distribution, and optimizing system operation to maximize energy efficiency.

The influence of installation depth and length has also been extensively investigated. Muehleisen et al. [145–147] proposed an optimal burial depth of less than 5 m for EAHE, considering the trade-off between construction costs and energy efficiency.

Table 2 outlines the key factors that significantly impact the performance of earth-air heat exchangers (EAHEs), encompassing climatic conditions, ground surface characteristics, and various design parameters.

Table 2. Effect of key parameters on the performance of EAHE.

Parameter	Effect on Performance	References
Climatic conditions:		
temperature	In regions with significant temperature variations between summer and winter, EAHEs can exhibit high performance in both cooling and heating modes. In hot and arid regions, EAHE systems can effectively cool incoming air. In cold climates, EAHE systems can preheat incoming air, reducing the heating load. However, extreme temperatures can lead to ground overheating or freezing in the vicinity of the collectors, potentially compromising long-term system efficiency.	[11,25,113–116],
precipitation and extreme weather events		
	Rainfall and snowmelt can influence soil moisture content, affecting thermal conductivity and heat transfer.	[115–117]
Ground surface conditions:		
vegetation cover	Vegetation cover can influence ground temperature by shading the soil and reducing the impact of solar radiation.	[51,94,111,113,114]
soil type	Impacts the thermal conductivity and heat capacity of the soil.	[71,72,98–100]
Design Parameters:		
pipe geometry (diameter, length, shape)		
	Increased diameter generally leads to higher heat transfer rates but can also increase pressure drop; longer pipes generally provide greater heat exchange area; rectangular and elliptical shapes can offer increased heat transfer surface area compared to circular shapes.	[126,128–130,133]
burial depth		
	Optimal depth varies depending on ground temperature gradient and site-specific conditions.	[145–147]
airflow rate		
	Higher airflow rates can improve heat transfer but also reduce efficiency due to shorter contact times. The optimal airflow rate depends on various factors.	[112,132]
pipe configuration (multi-pipe systems)		
	U-shaped configurations generally exhibit superior thermal performance compared to Z-shaped designs; uneven airflow distribution can significantly impact performance.	[135–144]

In recent decades, there has been a surge in interest in EAHE systems, driven by increasing concerns about energy efficiency and environmental sustainability. Researchers have explored various configurations and applications of EAHE, including hybrid systems that combine EAHE with other renewable energy technologies, such as solar, geothermal, and wind energy. The growing interest in hybrid EAHE systems is driven by several factors, including stringent energy efficiency standards, advancements in renewable energy technologies, and climate change mitigation.

4. Integration of EAHE with Renewable Energy Sources

4.1. EAHEs Integrating with Air-Source Heat Pumps (ASHPs)

The integration of Earth-to-Air Heat Exchangers (EAHE) with Air-Source Heat Pumps (ASHPs) has emerged as a promising strategy to enhance the energy efficiency and sustainability of building heating and cooling systems. This synergistic approach leverages the stable ground temperature provided by EAHEs to pre-condition the inlet air to the ASHP, leading to improvements in the system's coefficient of performance (COP) and an extended operating range. Recent research has explored various aspects of this integration, including system performance optimization, economic feasibility, and environmental impact. However, the performance of EAHE-ASHP systems is influenced by complex interactions between soil properties, climatic conditions, and system design parameters. Further research is needed to fully understand these interactions and optimize the design and operation of these hybrid systems.

Recent research has demonstrated the potential of integrating EAHEs with ASHPs to improve the energy efficiency of building heating and cooling systems. Studies such as those conducted by Congedo et al. [43], Guo et al. [148], Do et al. [149], Mahmoud et al. [150], and Cavazzini et al. [77] have shown promising results under various climatic conditions. Two primary integration methods have been explored: open-loop and closed-loop integration.

Open-loop systems involve a direct interface between the ambient air and the ground (Figure 6). When ambient air passes through buried pipes, heat exchange occurs with a relatively stable ground temperature, preconditioning the air before entering the ASHP [151]. This preconditioning significantly enhances the heat pump's coefficient of performance (COP), particularly during extreme weather conditions. Cavazzini et al. [77] conducted a comprehensive study to evaluate the performance of an air-source heat pump integrated with an earth-air heat exchanger (EAHE) in a single-family residence located in northern Italy. This study aimed to assess the system's efficiency under real-world operating conditions and quantify the benefits of coupling an EAHE with an ASHP. Although ASHPs traditionally transfer heat between air and water for space heating and cooling, this novel approach involves preconditioning the air by passing it through an EAHE before it enters the ASHP.

The EAHE, in turn, leverages the thermal inertia of the ground to mitigate fluctuations in air temperature, enabling the ASHP to operate more efficiently. The researchers employed a detailed simulation model developed in MATLAB (r2019a) to replicate the system's behavior. The model was calibrated and validated using the year's worth of operational data from the building. The analysis focused on two primary objectives: understanding system performance under real-world conditions and quantifying the advantages of integrating an EAHE. The results demonstrated that the integration of an EAHE significantly improved system performance. EAHE contributed approximately 50% of the total heating demand during winter, reducing the reliance on auxiliary heating sources. Furthermore, the EAHE ensured a relatively stable supply of air throughout the year, leading to a more efficient operation of the heat pump. A detailed analysis of the energy consumption

revealed that the system with the EAHE achieved a 25% reduction in energy consumption compared to a system without an EAHE. This was primarily due to the reduced operating hours of the heat pump and auxiliary heater.

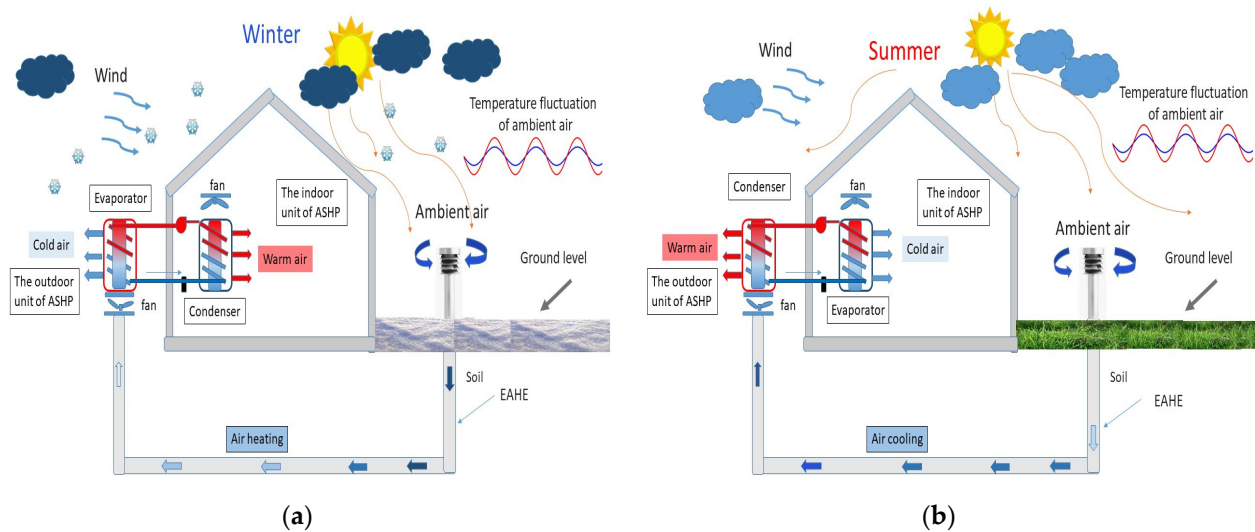


Figure 6. Open-loop EAHE integrated with an air-source heat pump: (a) in winter and (b) in summer.

Closed-loop systems harness Earth's low-grade thermal energy by circulating air through an underground network of pipes [80,152]. Schematic diagrams of the closed-loop EAHE system coupled with an air-source heat pump are shown in Figures 7a and 7b, respectively. Do et al. [149] integrated a closed-loop earth-air heat exchanger (EAHE) with an Air-source heat pump (ASHP) to cool residential buildings in the hot and humid climate zones of Texas, USA. The potential energy savings of this hybrid EAHE/ASHP system were evaluated by comparing simulations of ASHPs with and without buried pipes. The results indicated that the incorporation of an EAHE system yielded annual cooling energy savings of approximately 9.6% and 13.8% for Houston and Dallas, respectively. Despite these promising findings, the authors noted that their analysis was limited to energy consumption and savings and recommended further research to quantify the increased installation costs and reduced operating expenses of the system, thereby determining the extent to which these hybrid systems can be implemented in a cost-effective manner.

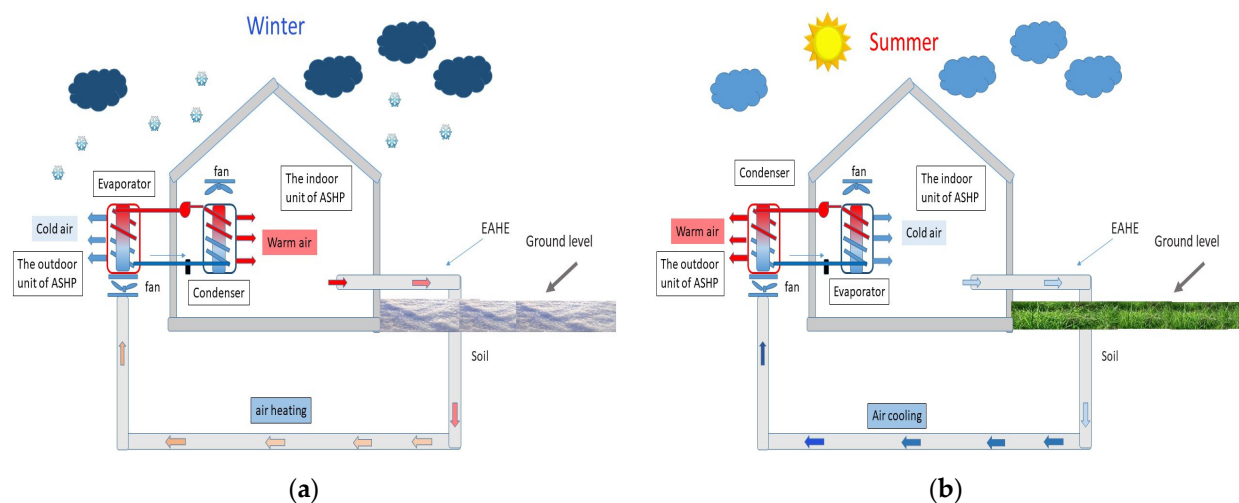


Figure 7. Closed-loop EAHE integrated with an air-source heat pump: (a) in winter and (b) in summer.

Although both systems offer distinct advantages, more research is needed to comprehensively evaluate their performance under various climatic conditions and develop optimized design guidelines. Factors such as pipe material, burial depth, and flow rate significantly influence the overall system efficiency and economic viability. Moreover, long-term monitoring and data analysis are essential for assessing the durability and reliability of these integrated systems.

4.2. EAHEs Integrating with Photovoltaic Systems

The integration of EAHEs with photovoltaic (PV) systems is a promising strategy for achieving significant improvements in building energy efficiency. Recent research has extensively explored the potential benefits of this synergistic approach, as evidenced by the studies conducted by Baglivo et al. [78], Kundu et al. [153], Dokmak et al. [154], Yadav et al. [155], Hraibet et al. [156], and Zhao et al. [157]. These hybrid systems offer several potential applications, including pre-cooling/pre-heating of supply air, temperature control for PV panels, the creation of hybrid energy systems, and the development of Combined Cooling, Heating, and Power (CCHP) systems (Figure 8).

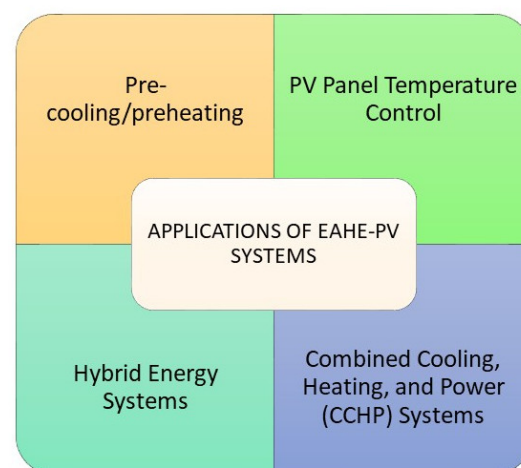


Figure 8. Applications of EAHE-PV systems.

A key advantage of integrating EAHEs with PV systems lies in their ability to pre-cool or preheat the supply air [158]. During the hot summer months, EAHEs can significantly reduce the load on building HVAC systems by providing pre-cooled air. On the contrary, during colder periods, preheated air from the EAHE can be used, minimizing the energy required for space heating. This preconditioning process demonstrably improves the overall efficiency of the HVAC system, leading to a substantial decrease in energy consumption [78]. The hybrid system described by Soares et al. [48] is aligned with the principles of sustainable building. The standalone photovoltaic system powers fans that circulate air through underground EAHE pipes, leveraging a stable ground temperature for preconditioning the outdoor air. This approach not only yields substantial energy savings but also enhances a building's independence from external energy sources.

Building-Integrated Photovoltaics (BIPVs) refer to photovoltaic modules that are integrated into the building envelope, such as the roof or facade. Unlike traditional photovoltaic systems, BIPV not only generates electricity, but also serves as a building component (Figure 9).

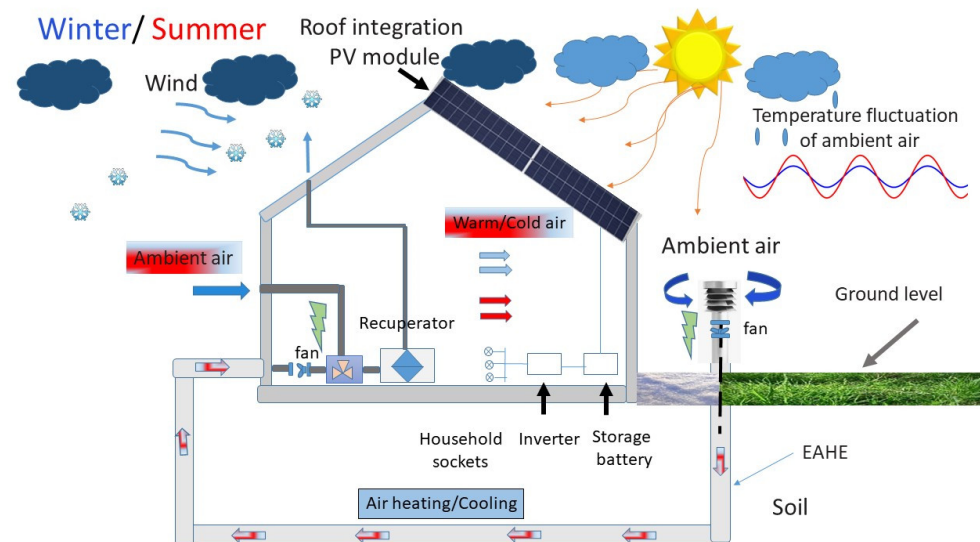


Figure 9. Hybrid system combining earth-air heat exchanger (EAHE) and roof-integrated photovoltaic systems (RIPV).

This dual functionality offers several advantages, including improved aesthetics, reduced installation costs, and enhanced energy efficiency [159,160]. However, BIPV systems are susceptible to overheating, which can significantly reduce their efficiency. The proposed hybrid system combines the benefits of both technologies. The EAHE pre-cools the supply air, which is then passed over the rear of the BIPV modules. This reduces the operating temperature of the photovoltaic cells, leading to increased electrical efficiency. Additionally, cooled air can be circulated within the building to provide thermal comfort. This approach not only improves the energy performance of the building but also reduces the overall environmental impact (Figure 10).

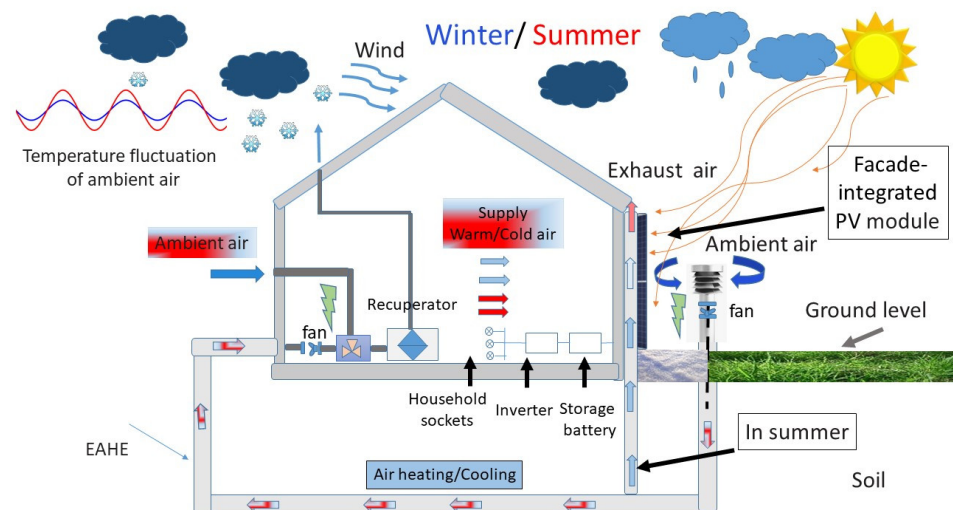


Figure 10. Hybrid system combining earth-air heat exchanger (EAHE) and facade-integrated photovoltaics (FIPVs).

Figure 11 illustrates a hybrid system integrating an earth-air heat exchanger (EAHE) with phase change material (PCM) ceiling boards for passive cooling. This system effectively regulates indoor temperature, improves energy efficiency, and enhances occupant comfort. Intended for regions where natural ventilation is not effective due to high outdoor temperatures, this system is suitable for hot and humid climates.

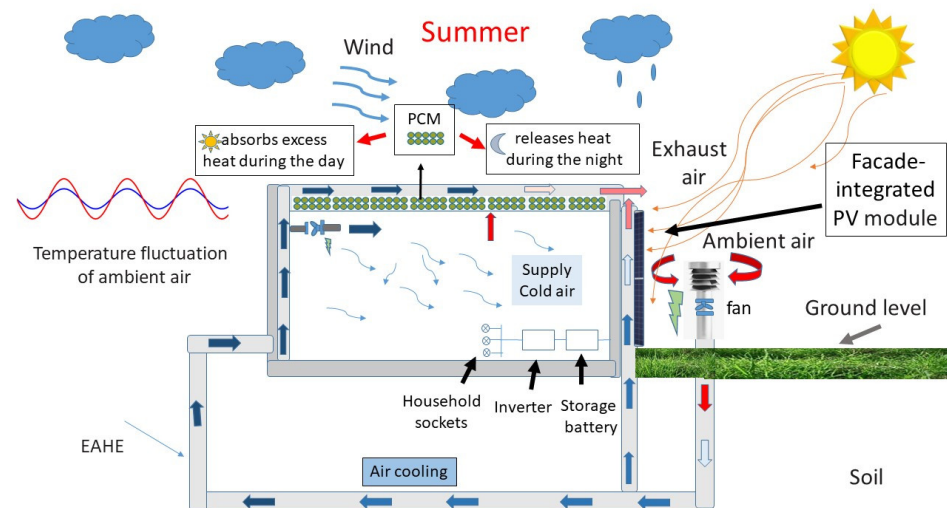


Figure 11. A hybrid system combining an earth-air heat exchanger (EAHE), facade-integrated photovoltaics (FIPV), and PCM.

As shown in Figure 11, the EAHE pre-cools the incoming air by drawing it through underground pipes, where it exchanges heat with the cooler ground. This pre-cooled air is then circulated through the building. PCM embedded in the ceiling boards absorbs excess heat during the day, preventing overheating, and releases this stored heat during the night, reducing temperature fluctuations. A fan facilitates air circulation, enabling heat exchange between the EAHE, PCM, and indoor environment. The system operates in various modes, including solely utilizing PCM for moderate heat gain, relying solely on the EAHE during cooler periods, and a combined mode for peak loads. This hybrid approach offers enhanced cooling capacity, improved indoor comfort, and reduced energy consumption by leveraging natural cooling sources and minimizing reliance on mechanical refrigeration.

Shahsavari et al. [75] evaluated the performance of a hybrid system that combines an earth-air heat exchanger (EAHE) and a building-integrated photovoltaic/thermal system incorporated with a phase change material (PCM). The system was designed to satisfy the heating, cooling, and electrical demands of a building located in Kermanshah, Iran. A multi-objective genetic algorithm (MOGA) was used to optimize system parameters such as the length (L), width (W), and depth (D) of the PCM, mass flow rate ($\dot{m}$), and depth and length of the EAHE (D_{EAHE} , L_{EAHE}), with the aim of maximizing thermal and electrical outputs. The optimal photovoltaic/thermal (HPT) system exhibited the highest electrical output in July and the lowest in December. The optimized system could supply 26,536.1 kWh of cooling load, 132,693.3 kWh of heating load, and 9242.2 kWh of electrical load to the building annually.

Numerous studies have investigated the performance of EAHE-PV hybrid systems. Photovoltaic panels exhibit reduced efficiency at higher temperatures. Using the cooling capacity of the EAHE, the ambient temperature surrounding the photovoltaic panels can be reduced, leading to increased power output and improved overall system efficiency [161]. For example, Dhaidan et al. [162] conducted a comprehensive review of the application of geothermal energy in agricultural solar greenhouses, highlighting the potential of EAHE to improve the overall system performance.

Jakhar et al. [163] conducted a comprehensive numerical investigation into the thermal performance of EAHEs integrated with photovoltaic thermal (PV/T) systems across three distinct locations: Pilani, Ajmer (India), and Las Vegas (USA). Their validated thermodynamic model demonstrated significant performance enhancements when incorporating cooling measures. Notably, the integrated system exhibited substantial increases in thermal

power across all locations compared to the PV/T system alone. This study highlighted the significant potential of these hybrid systems for improving building energy efficiency under diverse climatic conditions.

Finally, Lopez-Pascual et al. [164] proposed a compact cooling system for commercial photovoltaic panels based on low-enthalpy geothermal cooling. A single-phase closed-loop cooling system was used to dissipate heat from the solar panel using the constant and low temperature of the natural underground heat sink. A prototype incorporating a single-axis solar tracking mechanism was assembled and tested outdoors in Alcalá de Henares, Madrid, Spain, in June 2022. Experimental results demonstrated that with a coolant flow rate of 1.8 L/min per square meter of panel surface, the cooling system reduced the temperature of the cooled panel by up to 20 °C, leading to a real increase in panel efficiency of up to 13.8%.

4.3. Energy Systems EAHEs Integrated with Solar Energy

The increasing demand for sustainable and energy-efficient building solutions has spurred the development of innovative technologies. Hybrid systems that integrate renewable energy sources with traditional building systems have attracted considerable attention. Among these, solar chimney (SC) systems coupled with photovoltaic panels and earth-air heat exchangers (SC-PV-EAHE) offer a promising avenue for achieving thermal comfort while reducing reliance on conventional cooling systems (Figure 12).

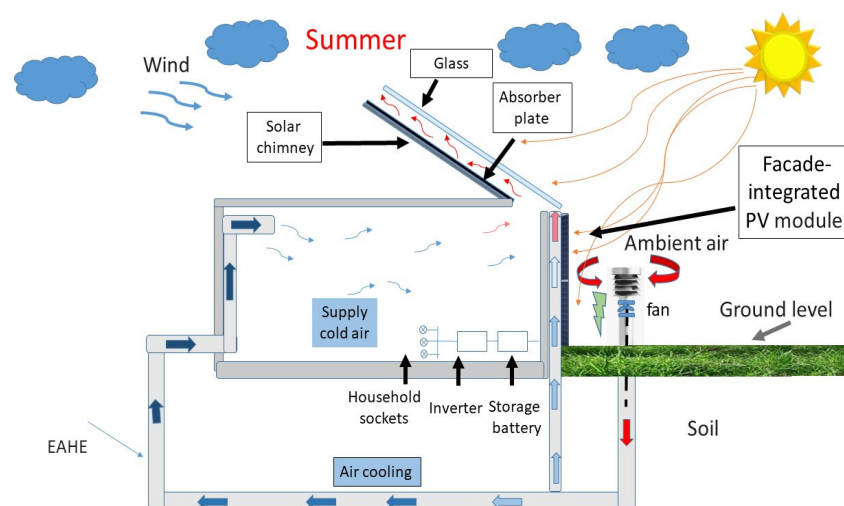


Figure 12. A Hybrid system combining an earth-air heat exchanger (EAHE), facade-integrated photovoltaics (FIPV), and SC.

In [165,166], experimental results from a solar greenhouse (SG) integrated with an EAHE and photovoltaic system were presented. In these studies, cooled air from the EAHE was circulated through the SG to create a more comfortable environment for plant growth, while simultaneously cooling the PV modules mounted on the greenhouse structure. Their findings demonstrated that the circulation of air through the EAHE before directing it to the SG significantly reduced the ambient temperature within the greenhouse, leading to a notable improvement in the PV panel efficiency. For example, Yildiz et al. [167] reported a temperature reduction of approximately 8 °C between the inlet and outlet of the EAHE, resulting in 31% energy savings. The integrated system not only improved the efficiency of the PV panels but also provided a sustainable cooling solution for the greenhouse.

Alkaragoly et al. [168] made a notable contribution to this field by demonstrating the feasibility and effectiveness of such a system in a residential setting. Their study revealed that the SC-PV-EAHE system could effectively satisfy the cooling loads while simultaneously generating a substantial amount of electricity. This research investigated the

performance of a novel hybrid system designed to provide thermal comfort and electricity generation for residential buildings. A comprehensive numerical analysis was conducted to evaluate the performance of the SC-PV-EAHE system under various climatic conditions. The study focused on two Middle Eastern cities, Tehran and Baghdad, which are known for their hot and arid climates. The EAHE system was modeled considering three primary heat transfer processes: convective heat transfer between the air flowing through the buried pipe and its inner surface, conductive heat transfer through the pipe wall, and conductive heat transfer between the pipe's outer surface and the surrounding soil. The optimal dimensions for the solar chimney and photovoltaic array were calculated based on the climatic conditions of each city. For instance, in Tehran and Baghdad, a chimney width of 2.4 m and a length of 4.216 m was recommended, accommodating 16 photovoltaic panels. Their findings underscored the system's effectiveness in achieving thermal comfort, with cooling demands ranging from 116 to 1500 W. Furthermore, the integrated photovoltaic panels generated a significant amount of electricity, with peak outputs reaching 1060 Watts in Tehran and 781 Watts in Baghdad. The system exhibited high electrical efficiency, with values of 9.7% for Tehran and 8.9% for Baghdad. The generated electricity can be used to power the building's electrical systems and improve the overall energy efficiency. These results not only validate the feasibility of such hybrid systems but also highlight their potential to reduce reliance on conventional cooling systems and contribute to sustainable building design.

The research presented in [52] offers a comprehensive evaluation of a hybrid solar chimney and EAHE system for passive building cooling in arid climates. This study investigated the performance of a novel hybrid system that combines solar chimneys and earth-air heat exchangers (EAHEs) for passive cooling in buildings located in hot, arid regions. Through a combination of experimental and numerical analyses, researchers have explored the intricate relationship between ventilation rates, solar chimney design parameters, EAHE geometry, pressure differentials, and climatic conditions. The study focused on two case scenarios: a baseline configuration with a solar chimney and EAHE, and a hybrid system that incorporates passive and active ventilation components. The results indicated that the proposed hybrid system significantly improved indoor thermal comfort, reducing zonal temperatures by up to 9 °C compared to the baseline case. The integration of electric fans into the hybrid system further improved the cooling performance and energy savings. Moreover, the system demonstrated substantial reductions in annual energy consumption and CO₂ emissions. Economic analysis revealed a relatively short payback period, highlighting the system's long-term economic viability.

Recent research by Li et al. [169] explored the potential of integrating solar chimneys, earth-air heat exchangers (EAHEs), and photovoltaic panels into a hybrid system for building applications. MATLAB (2017b (64-bit)) was used for the numerical modeling of the buried tubes, solar chimney, and photovoltaic panels, while the building model was developed using the TRNSYS 18 software, incorporating weather data and building modules. By systematically varying the number of EAHE tubes and solar chimney-photovoltaic modules, the researchers quantified the impact on key performance indicators, including ventilation rate, outlet air temperature, and electrical efficiency. A salient finding of this study was the substantial reduction in the peak daily ventilation rate achieved by the hybrid system compared to a standalone solar chimney system. Specifically, the integration of EAHEs led to a 22.05% decrease in the peak ventilation rate. Furthermore, the hybrid system demonstrated improved thermal performance, achieving an average reduction of 0.12 °C in the outlet air temperature. While indoor temperatures exhibited only minor variations between the hybrid and conventional ventilation systems, the hybrid system proved to be more energy efficient, showing a 1.34% enhancement in minimum electrical

efficiency compared to an independent photovoltaic system. Parametric analyses revealed distinct influences of the system components. Increasing the number of EAHE tubes resulted in a significant increase in forced ventilation (over 36.43%) and a concomitant decrease in the temperature of the outlet air. In contrast, increasing the number of solar chimney-photovoltaic modules primarily affected the supply air and outlet air temperature, with a negligible impact on the efficiency of the photovoltaic panels.

4.4. Advanced Applications: Cooling, Heating, and Power Systems

With increasing concerns about climate change and the environmental impact of conventional air conditioning systems, there is a growing demand for sustainable and energy-efficient cooling solutions. Several published studies in the literature have focused on improving cooling systems without efficiency reductions, including evaluations of their economic feasibility. Jang et al. [170] investigated a building-integrated EAHE retrofitted with a supplementary groundwater system in a cooling-dominated climate (Figure 13).

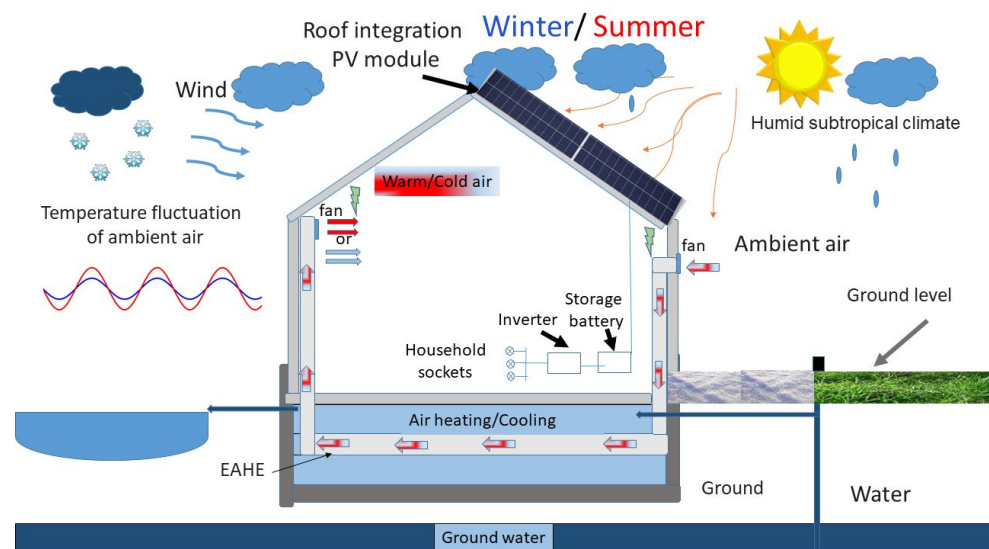


Figure 13. A hybrid system combining foundation-integrated water-based EAHE and Facade-integrated photovoltaics (FIPV).

This study investigated a foundation-integrated water-based EAHE (FIWEAHE) system enhanced by circulating supplementary groundwater from a residential well. Experimental and numerical results demonstrated significant performance improvements. After groundwater integration, the cooling capacity increased from 3.21 kW to 4.84 kW, and moisture removal rose from 1.97 kg/h to 4.24 kg/h during summer. The system effectively maintained indoor comfort, with summer outlet air temperatures between 24 and 26 °C and winter temperatures of 20–21 °C. The mean summer and winter COPs were 10.5 and 1.74, respectively. This study developed design relation curves to optimize pipe geometry and airflow velocity, providing valuable guidelines for the future design of the FIWEAHE system.

Research conducted by Ahmadi et al. [171] has shown that a hybrid system integrating EAHE and a water spray channel offers a promising solution for sustainable building cooling in the Tehran climate. In this study, the authors critically analyzed the system's effectiveness in providing thermal comfort and its environmental benefits within the context of the Tehran climate. According to the results, the cooling effectiveness of the proposed hybrid system exceeds 100%, indicating the system's capability to decrease the air dry-bulb temperature below the inlet ambient wet-bulb temperature. By effectively using the ground as a reliable source of alternative energy, this cooling system can be considered both

ecofriendly and energy efficient. Consequently, the introduced system presents a viable alternative to conventional evaporative coolers or mechanical vapor compression systems.

The industrial applications of EAHEs are diverse and encompass a wide range of sectors. These include pre-cooling for air-cooled condensers and air compressors, dry cooling for thermal power plants, and cooling applications for advanced power generation systems, such as those employing supercritical Rankine cycles and gas turbines. Figure 14 shows the integration of an EAHE with a gas turbine power plant. The performance is significantly influenced by the ambient temperature, particularly during the summer months, which can lead to imbalances in the power supply and demand [172,173]. Inlet air cooling is crucial for maintaining high-efficiency power generation. Common inlet air cooling methods include direct evaporative cooling and electric refrigeration. Although electric refrigeration offers a significant reduction in temperature, it requires substantial energy consumption. In contrast, direct evaporative cooling cools air through water evaporation, but its effectiveness is highly dependent on the ambient air temperature and relative humidity. In hot and arid regions, direct evaporative cooling offers economic advantages over electric refrigeration.

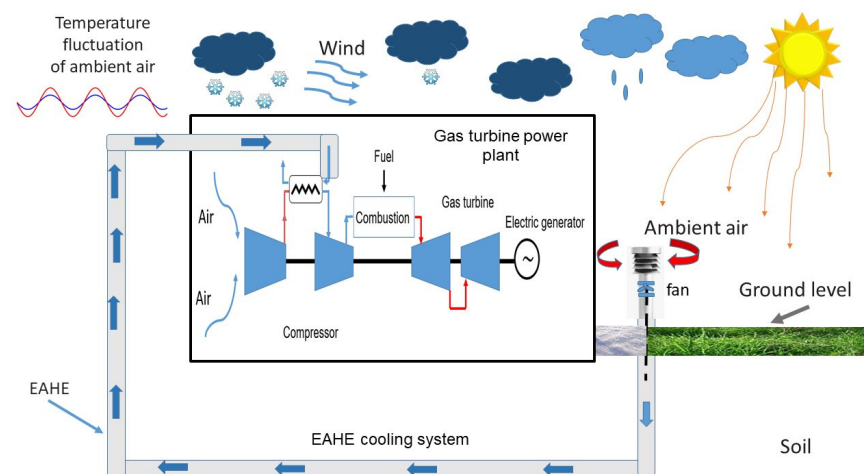


Figure 14. Gas turbine power plant with integrated EAHE for interstage air cooling.

Barakat et al. [174] investigated a novel hybrid inlet air cooling system for gas turbines, integrating an EAHE with a fogging system. Their comparative study in a 125 MW gas turbine unit demonstrated significant performance improvements. The annual average power output of the gas turbine equipped with the hybrid cooling system exhibited a 9.8% increase compared to the uncooled unit, while the fogging system alone resulted in a 6.6% increase. In particular, the hybrid system achieved a 50% reduction in water consumption compared to the fogging system during periods of high ambient temperatures.

A previous study [175] introduced a novel approach to cooling solar thermal power plants by utilizing earth-cooling air tunnels (Earth CATs) as a means to reduce water consumption. This research leverages the principle of existing earth-air heat exchangers (EAHEs) by exploiting the stable and relatively low underground temperature to pre-cool ambient air before it enters the plant's air condenser. A comprehensive computational fluid dynamics (CFD) analysis was conducted to assess the feasibility of this innovative cooling system and investigate the sensitivity of various geometric and flow parameters to optimize performance. The results demonstrated that a configuration employing pipes with a diameter of 0.5 m and an approximate length of 300 m is technically viable and offers a promising zero-water alternative to conventional water-cooling technologies. This study contributes to a growing body of research on sustainable and water-efficient cooling solutions for thermal power plants.

Benhammou et al. introduced a novel design of a passive cooling system consisting of an EAHE supported by a wind tower (Figure 15). The results demonstrated that the ambient air passing through the wind tower connected to the EAHE exhibited lower temperatures compared to the air exiting a conventional cooling tower.

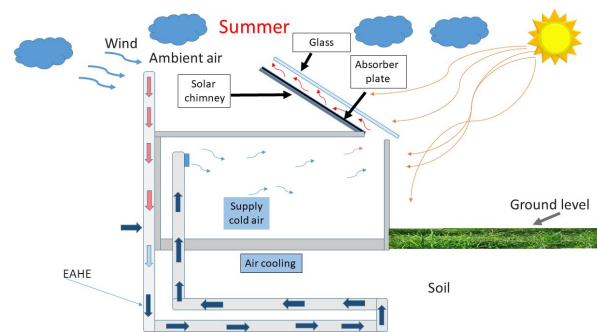


Figure 15. Integrated EAHE and wind tower for building cooling.

Shahsavari and Arici [176] investigated a novel hybrid system that integrated photovoltaic thermal (PVT) panels and an earth-air heat exchanger (EAHE) for building heating and cooling. This system harnesses both solar and geothermal energy to condition the outdoor air before it enters the building's HVAC system, while simultaneously generating electricity. The study used a genetic algorithm to optimize the annual energy and exergy output of the system. The proposed system consists of a PVT panel and an EAHE.

During the cooling season, outdoor air is passed through the EAHE to reduce its temperature, while return air from the building is used to cool the PVT panels. In contrast, during the heating season, the outdoor air is preheated by passing through both the PVT panels and the EAHE. The research findings revealed that while the combined PVT-EAHE system produced slightly less annual energy (93,925.6 kWh) compared to a standalone PVT-EAHE system (96,448.6 kWh), it exhibited a higher exergy output (10,904.5 kWh) compared to the standalone system (10,015.5 kWh). This indicates that the hybrid system offers improved thermodynamic efficiency despite a slight reduction in overall energy production.

5. Conclusions

This comprehensive review delves into the latest advancements in earth-air heat exchanger (EAHE) technology, with a particular focus on their application in buildings and industrial settings. By synthesizing the findings of recent studies, this review highlights the significant potential of EAHEs as a sustainable and energy-efficient solution for building climate control. Based on the analysis of the different EAHE integration studies summarized in Table 3, it is clear that the integration of EAHE with other renewable energy technologies is a promising way to achieve high energy efficiency and significantly reduce the environmental impact of building operations. EAHE systems offer a viable and sustainable alternative to traditional HVAC systems by leveraging the relatively constant temperature of the subsurface. By pre-cooling or pre-heating ventilation air, EAHEs can significantly reduce energy consumption and lower operational costs. Moreover, the integration of EAHEs with other renewable energy sources, such as air-source heat pumps, photovoltaic thermal (PVT) panels, wind towers, fogging systems, water spray channels, solar chimneys, and photovoltaic systems, has demonstrated enhanced performance and reduced environmental impact. The performance of EAHE systems is influenced by a multitude of factors, including soil properties, climatic conditions, system design, and operational parameters. A thorough understanding of these factors is essential to optimize the design of the system and predict performance accurately.

Table 3. Summary of EAHE systems and integrating technologies.

Type of System	Reference	Location	Configuration Parameters	Primary Benefit	Main Results	Improvement	Energy Efficiency
standalone EAHE; open loop, without external devices; experimental techniques	[177]	Bechar (arid regions located in the Southwest of Algeria)	PVC pipe, 66 m long and 110 mm in diameter; buried at a depth of 1.5 m in an agricultural area; annual undisturbed subsoil temperature at a 1.5 m depth of 28 °C	space heating/cooling	raise the air temperature by 10 °C in the heating regime and reduce it by 11.9 °C in the cooling regime	dependent on ground temperature, depth, and system design	significant performance capabilities, achieving a maximum temperature rise of 10 °C in heating mode and a maximum temperature drop of 11.9 °C in cooling mode; a maximum relative humidity rise of 19% in humidification mode and a maximum drop of 27% in dehumidification mode; different daily operating regimes: heating and dehumidification predominant in colder periods (00:00–08:00 and 18:00–23:00) and cooling and humidification predominant in warmer daytime hours (09:00–17:00); effective climate control in different environmental conditions
standalone EAHE, open loop; experimental and numerical modeling techniques	[17]	Bucaramanga, Colombia (tropical climate)	simulations used a PVC pipe ($k = 0.185 \text{ W/m}\cdot\text{K}$) buried at 1.5 m depth; reference case with a 60 m length, 0.2 m diameter, and 1240 kg/h flow rate was established; each parameter (mass flow rate: 620, 1240, 1860 kg/h; diameter: 0.1, 0.2, 0.3 m; length: 90, 150, 200 m) was varied independently while others remained constant	reduction of building cooling load	optimal EAHE configuration determined: 252 m length (7 pipes in parallel), 0.2 m diameter; achieved air temperatures between 20.9 °C and 24.1 °C; meeting thermal comfort requirements	dependent on local climatic conditions and soil properties; potential for wider adoption of EAHE technology in similar tropical environments	the maximum cooling capacity is 11.9 °C and the maximum heating capacity is 10 °C; with a maximum COP of 160 and an energy-efficient fan system (0.12 kW per motor), the system significantly outperforms conventional HVAC systems; the effectiveness of the EAHE system in reducing cooling loads will depend on the specific climatic conditions and soil characteristics of the location where it is installed; variations in these factors can influence the system's performance and may require adjustments to the design or operating parameters to achieve optimal results

Table 3. Cont.

Type of System	Reference	Location	Configuration Parameters	Primary Benefit	Main Results	Improvement	Energy Efficiency
Vertical Earth-Air Heat Exchanger (VEAHE) with integrated tubular phase change material (PCM); experimental and numerical modeling techniques	[62]	China (subtropical monsoon climate)	vertical borehole configuration with integrated PCM tubes; tube depth was varied within a range of 12 m to 24 m; PCM container diameter: 50 mm and 150 mm	enhanced thermal performance of the VEAHE system; reduced air temperature fluctuations at the outlet; increased average cooling capacity; smaller occupied area compared to traditional VEAHE systems	significant reduction in air temperature peak and fluctuation at the outlet with increasing tube depth; PCM thermal conductivity had a noticeable impact on performance at larger container diameters (150 mm); optimal container length for the system was found to be 12 m	- improved thermal stability of the system; - enhanced system performance through reduced air temperature fluctuations and increased cooling capacity	demonstrated significant performance enhancements, reducing peak air temperature at the outlet by 4.73 °C (from 25.74 °C to 21.01 °C) and significantly diminishing temperature fluctuations from 3.59 °C to 0.62 °C as the tube depth increased from 12 m to 24 m, improving the system's efficiency and reducing temperature fluctuations, the integrated PCM system has the potential to reduce energy consumption associated with cooling operations;
EAHE and ASHP	[77]	single-family building in North Italy (continental climate)	passive house construction with high insulation levels; ASHP unit (model: Nilan Compact P); EAHE for pre-heating/pre-cooling; passive heat recovery exchanger; electric heater for peak demand, monitoring system	- reduced energy consumption compared to operation without the EAHE; - enhanced indoor comfort by maintaining stable indoor temperatures	the significant impact of air humidity on heat pump performance	- enhanced system performance and efficiency through the integration of the EAHE; - indoor comfort by providing more stable and consistent indoor temperatures	significantly enhanced system performance, reducing energy consumption by 30% in winter and ensuring adequate cooling capacity during summer compared to a scenario without the heat exchanger while maintaining unit efficiency close to design values
EAHE and ASHP; (closed-loop EAHE integrated with the return-air duct system); simulation software DOE-2.1e version 119	[149]	Texas, USA (residential buildings in hot and humid climates)	- integration of the return-air duct system with the ground; simulation model varied parameters such as EAHE pipe length, buried pipe depth, airflow velocity; EAHE system: pipe length from 15.2 to 91.4 m; buried depth: 1.8 m, 2.7 m, 3.7 m, 4.6 m; airflow velocity from 5.8 m/s to 2.9 m/s; validated the simulation model by comparison with experimental data from previous studies	reduced cooling energy consumption in residential buildings	longer pipe lengths and deeper burial depths generally increased cooling savings; reduced airflow velocity led to increased cooling energy savings; deeper burial depths beyond 3.7–4.6 m offered diminishing returns; locations with lower ground temperatures (like Dallas) showed greater potential for energy savings	enhanced energy efficiency of residential cooling systems; reduced reliance on conventional cooling methods, potentially leading to lower energy costs and reduced environmental impact	demonstrated significant annual cooling energy savings of 9.6% in Houston and 13.8% in Dallas when integrating a closed-loop EAHE system with a residential ASHP, with the greatest savings observed during the early cooling season (May–July); the EAHE system's cooling performance was improved by utilizing longer pipe lengths, deeper ground levels, and slower airflow velocities;

Table 3. Cont.

Type of System	Reference	Location	Configuration Parameters	Primary Benefit	Main Results	Improvement	Energy Efficiency
EAHE and PV	[163]	Pilani and Ajmer (India), Las Vegas (U.S.)	integration of an EAHE with a rooftop PV/T system	combined power and heat generation from the PV/T system	improved EAHE heating capacity with PV/T integration; significant reduction in PV cell temperature with cooling; feasibility of hybrid system in different climatic conditions	enhanced thermal performance of the EAHE system, increased system efficiency, and reduced reliance on conventional heating sources	the integration of PV/T collectors with the EAHE system resulted in a substantial reduction in cell temperature, with a maximum decrease of 10.9 °C observed in Las Vegas; the heating power increase varied significantly between locations, ranging from 23.47 to 298.74 Wh in Pilani and 41.43 to 270.75 Wh in Las Vegas; improved energy efficiency by utilizing solar energy to enhance the performance of the EAHE; potential for reduced reliance on fossil fuels for space heating;
PV-assisted EAHE for greenhouse cooling	[167]	solar Energy Institute, Ege University, Izmir, Turkey	- PV cell capacity 0.9 kW; air blower capacity 736 W; air flow rate 5300 m ³ /h	increased PV efficiency, greenhouse cooling	average EAHE exergetic efficiency 56.3%; average PV cell exergetic efficiency 4.94%; average air blower exergetic efficiency 63.1%; overall system exergetic efficiency 23.6%; maximum EAHE exergetic efficiency: 59.6%; maximum air blower exergetic efficiency 70.7%; maximum overall system exergy efficiency 32.2%	improved system efficiency through new technologies; 12-month performance monitoring recommended	The experimental results demonstrated significant energy savings, achieving 2.84 kWh and a 31% reduction in energy consumption using a 0.9 kW solar photovoltaic system. The overall system exergy efficiency reached a maximum of 32.2% at 02:20 PM, with component efficiencies of 59.6% for the EAHE, 70.7% for the air blower, and 4.94% for the solar photovoltaic cells; further research is needed to optimize system performance and explore avenues for improving exergetic efficiency through advancements in component technologies
SC-PV-EAHE hybrid system	[168]	Baghdad and Tehran climates	- 16 PV panels integrated into the solar chimney; EAHE system (Tehran: 1 system with 25 m length and 0.5 m radius pipe; Baghdad: 2 systems with 25 m length and 0.5 m radius pipe); solar chimney dimensions: width 2.4 m length of 2 PV panels; length 4.216 m (width of eight panels); air channel width: 0.3 m.	achieve thermal comfort in buildings, produce electricity, and utilize renewable energy sources	the SC-PV-EAHE system can achieve thermal comfort for cooling demands ranging from 116 W to 1500 W; electricity generation at 12:00: Tehran: 1042 W; Baghdad: 768 W; the feasibility of the system in hot climates	the study provides a foundation for further research and optimization of the SC-PV-EAHE system for different climates and building types	this configuration effectively met the cooling demands of the residential room, ranging from 116 to 1500 W, while generating peak electrical power of 1060 W in Tehran and 781 W in Baghdad, demonstrating the system's potential for both thermal comfort and electricity generation; the system effectively utilizes solar energy for both cooling and electricity generation; further research is needed to assess the system's performance in other climates and building types

Table 3. Cont.

Type of System	Reference	Location	Configuration Parameters	Primary Benefit	Main Results	Improvement	Energy Efficiency
EAHE and solar chimney	[169]	numerical study, applicable to various locations	- number of EAHE pipes; quantity of solar chimney-photovoltaic modules	simultaneous ventilation, cooling, and electricity generation for buildings	reduced peak daytime ventilation compared to a system without PV integration; slight reduction in outlet air temperature; minimal difference in indoor temperatures between the hybrid and ventilation-only systems; improved electrical efficiency compared to standalone PV systems; increasing EAHE pipes significantly increases ventilation volume and slightly improves electrical efficiency; increasing solar chimney-PV modules increases ventilation and outlet air temperature, but has minimal impact on temperature and electrical efficiency of PV panels	optimizing the design and operation of the hybrid system by considering factors like the number of EAHE pipes and solar chimney-photovoltaic modules	the hybrid system demonstrated a significant reduction in peak daytime ventilation rate by 22.05% compared to the standalone solar chimney system while simultaneously improving the minimum electrical efficiency by 1.34% compared to an independent photovoltaic system; potential for efficient energy utilization by combining ventilation, cooling, and electricity generation; improved electrical efficiency compared to standalone PV systems
EAHE and groundwater (FIWEAHE)	[170]	Taiwan (Cooling-dominated climate)	- the system utilizes a blower with a volumetric flow rate of 738.4 m ³ /h and a power consumption of 0.46 W; four EAHE are employed, each with an average length of 40 m and a diameter of 0.2 m; the pipes are spaced 0.1 m apart and buried at a depth of 1.3 m; a gradient of 0.3–0.05 m is incorporated for proper drainage; the pipes are configured in a U-shape for efficient water flow	improved building cooling performance; reduced energy consumption for air conditioning; enhanced indoor thermal comfort	summer COP from 10.5 to average, maximum 17.4; winter COP 1.74; outlet air temperature: 24–26 °C (summer) and 20–21 °C (winter); non-uniform air distribution observed at low airflow velocities	reduced excavation costs by integrating EAHE with the building foundation	high summer COP (10.5); significant improvement in cooling capacity and moisture removal with water supplementation

Table 3. Cont.

Type of System	Reference	Location	Configuration Parameters	Primary Benefit	Main Results	Improvement	Energy Efficiency
EAHE and fogging system	[174]	New Damietta power plant, coastal region of Egypt	EAHE: bank of parallel pipes with length and inner diameter buried underground; fogging system: atomizes water into micro-scaled droplets; hybrid system: combines EAHE with a subsequent fogging stage.	enhance gas turbine performance by cooling inlet air; increase power output and efficiency, and reduce water consumption compared to fogging-only systems	hybrid system boosts average annual energy output by 9.8% compared to 8% for fogging and 6.6% for EAHE alone; reduces water consumption by 50% compared to the fogging system; most efficient in regions with temperatures exceeding 30 °C and relative humidity below 60%	the potential of hybrid cooling systems for improved gas turbine performance and reduced water consumption	the hybrid cooling system exhibited the highest performance, increasing average annual energy output by 9.8% compared to 8% for fogging and 6.6% for the EAHE system alone while simultaneously reducing water consumption by 50% compared to fogging. This system is particularly well-suited for regions with ambient temperatures exceeding 30 °C and relative humidity below 60%; the impact of various factors (e.g., soil properties, groundwater levels, ambient conditions) on system performance may require further investigation
- PVT-HP-EAHE system (hybrid building-integrated PVT-heat pipe and EAHE)	[176]	General applicability	PE system (PVT-Heat Pipe only); PHE system (PVT-Heat Pipe + EAHE)	simultaneous heating/cooling of building air and electricity generation; improved energy and exergy efficiency compared to individual systems	PE system (PVT-Heat Pipe only): higher thermal energy and thermal exergy outputs, lower electrical energy output compared to PHE, annual useful energy: 96,448.6 kWh, annual useful exergy: 10,015.5 kWh; PHE System (PVT-Heat Pipe + EAHE): higher electrical energy output, lower thermal energy and thermal exergy outputs compared to PE, annual useful energy: 93,925.6 kWh, annual useful exergy: 10,904.5 kWh	higher exergy than standalone PVT; hybrid approach combining PVT-HP and EAHE for enhanced system performance	the PHE system demonstrated higher electrical energy output (10,126.0 kWh) compared to the PE system (9223.3 kWh); the PE system exhibited superior thermal and exergy performance, achieving 70,828.2 kWh of thermal energy and 10,015.5 kWh of exergy compared to 65,797.9 kWh and 10,904.5 kWh for the PHE system, respectively

The complex interactions between the heat and mass transfer within EAHEs have been explored in detail, providing valuable insights for future research and development. The key findings of this review underscore the potential of EAHEs to contribute to a more sustainable built environment. However, more research is needed to address challenges such as optimizing the system design for various climatic conditions, developing accurate predictive models, and evaluating the long-term performance and durability of EAHE systems. Building on the foundation of existing research, the field of EAHE technology can continue to advance and offer innovative solutions for sustainable building design.

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