Review

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Earth-Air Heat Exchangers: A Comprehensive Review

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

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Earth-Air Heat Exchangers: A Comprehensive Review

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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. The 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 synergistic 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.

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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 this 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], the global energy consumption in buildings has been steadily increasing over the past decade. In 2022, the sector consumed approximately 1% more energy than 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 total energy use in 2022, up from 30% in 2010. This shift towards 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 fuel 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, 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 driven up the demand for heating [8–11]. The impact of climate change is

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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 urbanisation 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 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 the design and operation. Their roots can be traced back to ancient civilisations who recognized the thermal properties of the Earth and used them for various purposes [16]. However, the modern concept of 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 ground and air. Pioneer studies investigated the thermal properties of different types of soil, the impact of pipe configuration, and the optimal design parameters for EAHX 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 to conclude that interest on the 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 application 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, EAHE contributes to improved thermal comfort and reduced energy consumption. Their applications are diverse, covering space heating and cooling[26–29], ventilation [20–22], process cooling [30], and agricultural climate control [31]. By pre-heating or pre-cooling incoming air, EAHE reduce the load on conventional HVAC systems. In addition, they provide fresh, filtered air, improving indoor air quality. According to [32–34], the implementation of EAHE systems demonstrates significant potential as an effective passive cooling and heating technology, particularly in 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 EAHE, achieving significant energy savings compared to conventional HVAC systems. These types of solutions have the potential to increase the efficiency of energy buildings and reduce CO_2 emissions.

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

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As technology continues to advance, EAHE systems are becoming more sophisticated and efficient. Innovative design approaches, such as the use of advanced materials and intelligent control systems, are further enhancing 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 EAHE, several challenges remain. These include the high initial investment costs, the impact of soil conditions on system performance, and the potential for system degradation over time. Future research should focus on addressing these challenges and exploring innovative solutions to improve 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. This review aims to provide a comprehensive overview of the principles, design, and performance of hybrid EAHE systems, with a particular focus on their potential for reducing energy consumption and greenhouse gas emissions. By addressing these objectives, this review will contribute to the advancement of sustainable building technologies and support the transition towards a more energy-efficient and environmentally friendly built environment. Additionally, the review will identify research gaps and propose future directions for the advancement of this technology.

2. Materials and Methods

This study employed a comprehensive literature review approach to explore the state of the art in 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 16324 scientific papers, which 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).

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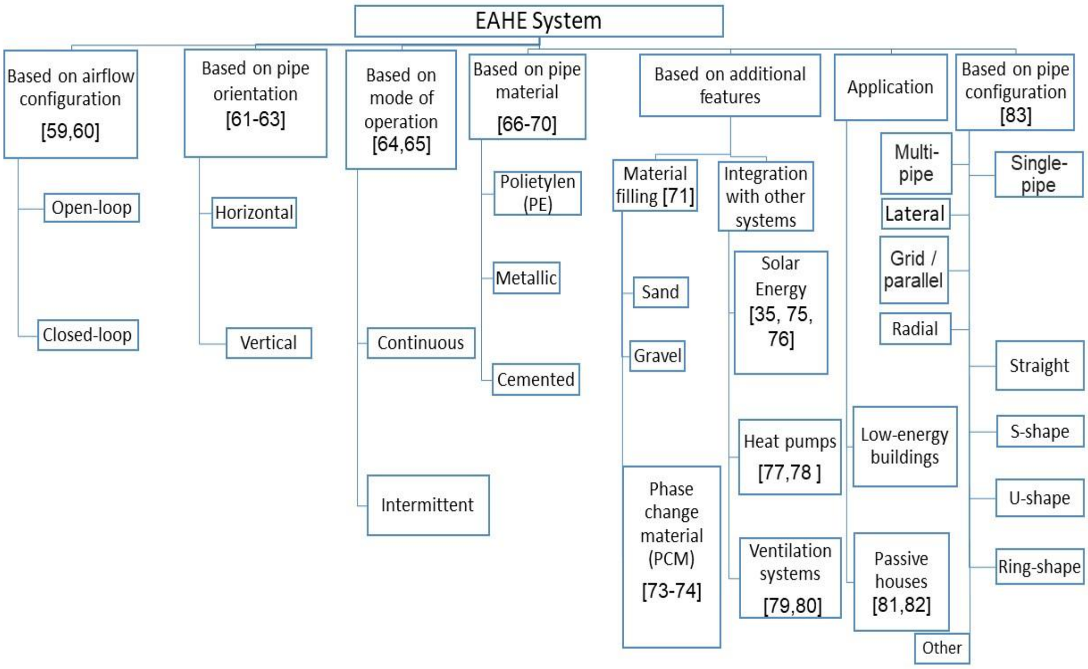
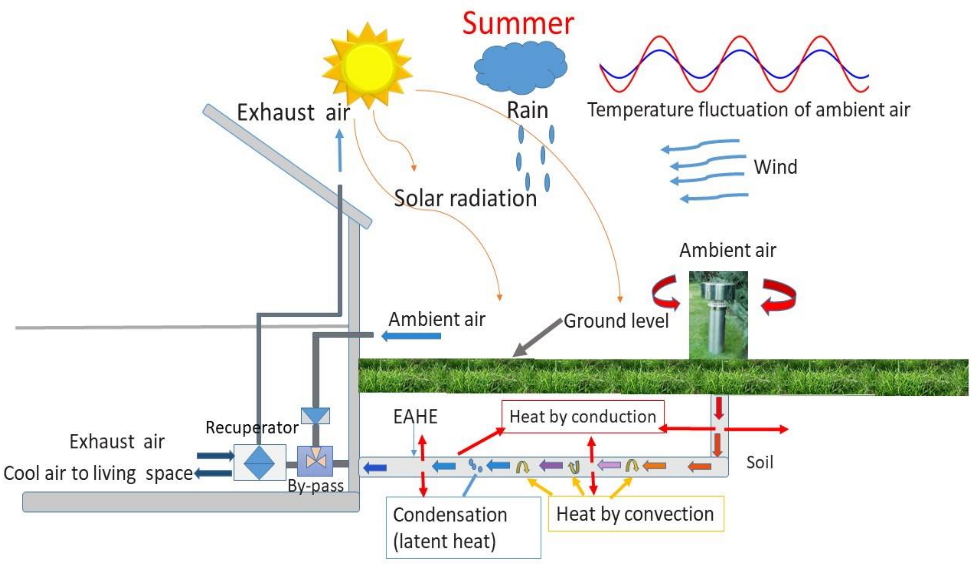


Figure 1. Classification of EAHE systems.

When the 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 the 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, subsequently being delivered to the indoor environment for ventilation purposes.



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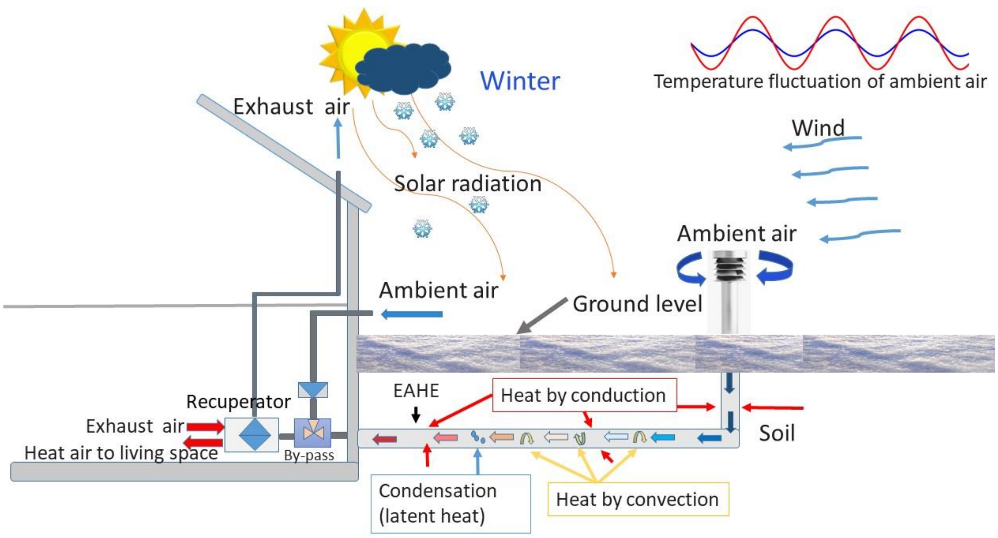

(**b**)

Figure 2. Working Principle of Earth-Air Heat Exchangers (EAHE) coupled with heat recovery units: (**a**) In summer; (**b**) In winter [84,85].

During summer (Figure 2(a)), the warm ventilation air dissipates heat to the surrounding soil, undergoing a pre-cooling process before entering the indoor space. Conversely, in winter (Figure 2(b)), the cool ventilation air can absorb heat from the surrounding soil, resulting in preheating. Although 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 [86].

Vertical systems are often preferred for urban or built-up areas where land is limited, and for applications requiring higher heat transfer rates [87]. They involve drilling boreholes into the ground and circulating air through a buried pipe network [88]. Vertical Earth-Air Heat Exchangers (VEAHEs) offer several key advantages over their horizontal counterparts by accessing deeper ground temperatures [89]. By accessing deeper ground temperatures, VEAHEs minimize the impact of near-surface temperature fluctuations caused by diurnal and seasonal variations. This results in more consistent and reliable heat transfer throughout the year, improving overall system performance [90]. By accessing deeper ground temperatures, VEAHEs minimize the impact of near-surface temperature fluctuations caused by diurnal and seasonal variations. This results in more consistent and reliable heat transfer throughout the year, improving overall system performance. VEAHEs are less affected by variations in near-surface soil temperatures caused by weather conditions (e.g., solar radiation, precipitation) or changes in soil moisture content. This leads to more predictable and stable system operation [88,91]. However, vertical EAHE systems also present certain challenges. Drilling boreholes typically incurs 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 risks of borehole collapse. Additionally, vertical systems may not be feasible in areas with high groundwater levels, limited space for borehole installation, or in regions with high seismic activity. In conclusion, both horizontal and vertical EAHE systems offer viable solutions to improve energy efficiency. The optimal choice depends on a variety of factors, including

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site-specific conditions, project budget, desired thermal performance, and environmental considerations. A thorough site assessment and a 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 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) involve complex interactions between buried pipes, surrounding soil, and supply air (Figure 3).

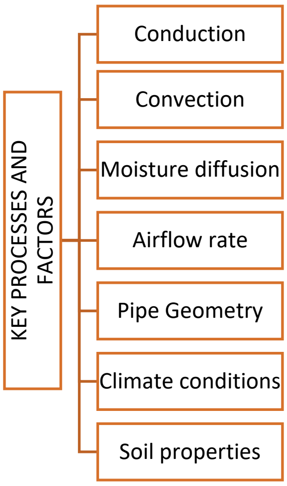

Figure 3. Key mechanisms and parameters affecting heat and mass transfer in EAHEs.

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).

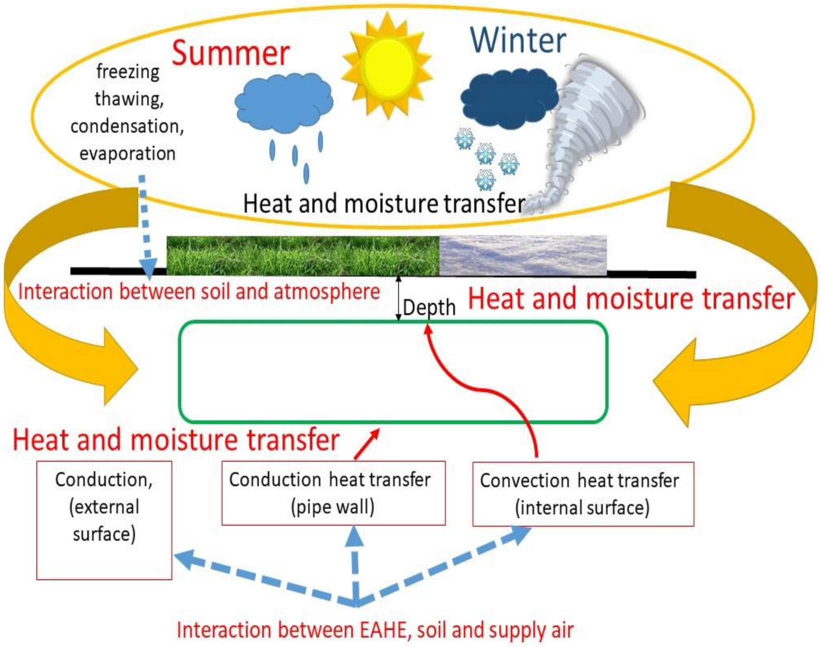

Figure 4. Heat and mass transfer in EAHE.

At the outer surface of the buried pipe, heat is conducted from the wall of the pipe into the surrounding soil and is governed by Fourier's law of heat conduction [92,93]. The rate of heat transfer is influenced by the thermal conductivity of the soil, its moisture content [94,95], and the temperature

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gradient between the pipe and the undisturbed soil. Additionally, moisture can diffuse between the soil and the pipe wall, depending on relative humidity and temperature gradients. At the inner surface, heat is transferred convectively between the wall of the flowing air and the pipe [96]. The rate of convective heat transfer is influenced by factors such as air velocity, the temperature difference between air and the pipe wall, and the 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 capacity of the 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 different climatic regions.

Accurate modeling of heat and mass transfer in earth-air heat exchangers is essential for their effective design and optimization [97]. 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 profile, and system design parameters (Figure 5).

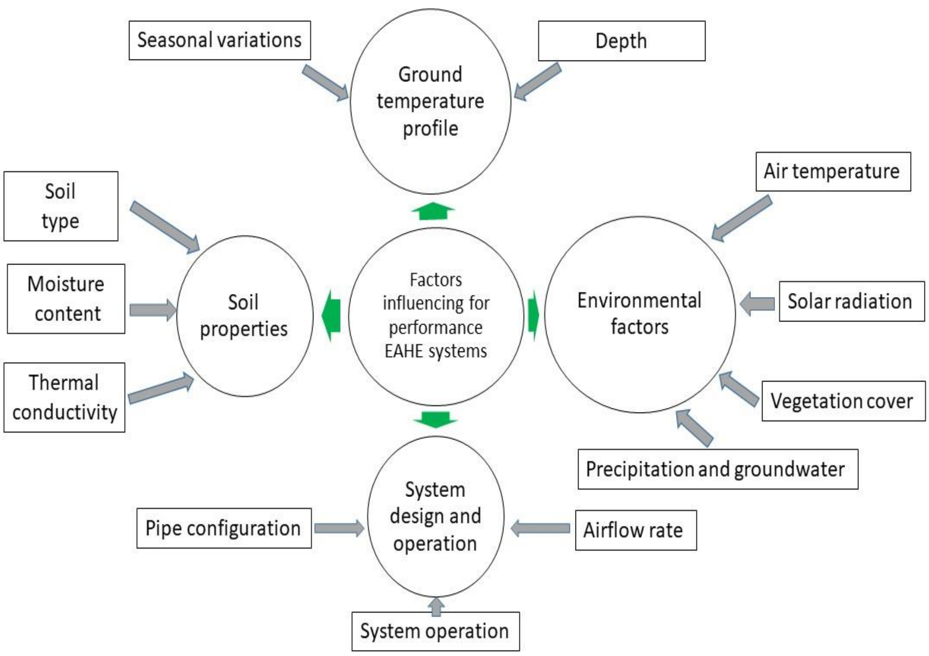

Figure 5. Factors influencing ground energy storage for EAHE system operations [98].

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 drew attention to such issue, showing how soils with higher thermal conductivity, such as clay-rich soils, generally exhibit better heat transfer compared to sandy soils [71,72,99]. 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 [100,101]. However, excessive moisture can have detrimental effects. High moisture content can lead to increased soil density, which can hinder heat transfer. Moreover, it can contribute to corrosion of buried pipes, compromising the longevity and efficiency [102].

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 depth [103,104]. Determining the optimal burial depth for EAHE systems is crucial to maximise system performance while minimising installation costs. Numerous studies [20,105,106] have observed a distinct temperature gradient, with temperatures decreasing as depth increases. This phenomenon creates a "zone of constant temperature" at a specific depth, usually ranging from 5 to 15 meters [107]. 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 [108] observed that depths greater than 3.5 metres offer minimal incremental performance gains compared to 3.5 meters. However, the optimal burial depth varies depending on location and site-specific factors. For example, [109] found an optimal depth of 1 metre in Malaysia, while Babar et al. [110] reported 3.96 meters as suitable for Sahiwal, Pakistan, and Khan et al. [111] suggested 4.5 meters 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.

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 [51,95,112] the performance of EAHE systems beneath grass and concrete surfaces was compared in 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. Beyond climatic factors, the nature of the ground surface also plays a crucial role. While 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 [113]. The interaction between ground surface and atmospheric temperatures, as emphasised by [114] and [115], 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 focus 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 thermal conductivity and alter the heat transfer mechanisms in the subsurface [116]. Moreover, snow cover can act as an insulating layer, affecting heat exchange between the ground and the atmosphere. Studies by Zajch et al. [117]. have 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. [118] provide more accurate predictions of the impacts of climate change scenarios on ground temperatures 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.

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). Modelling 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 modelling EAHE systems, such as EnergyPlus and TRNSYS, 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 [119–126]. For instance, Haitham Sghiouri et al. [127] proposed a multi-objective optimization framework to design efficient and cost-effective Earth-Air Heat Exchanger (EAHE) systems. Their framework, validated through an experimental exchanger model, identified key design parameters and employed a genetic algorithm for optimization. The optimization aimed to minimize life-cycle cost (LCC) while maximizing 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 emphasised the importance of site-specific design, as optimal configurations varied depending on factors such as 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 thermal performance and indoor air quality of Earth-Air Heat Exchangers (EAHE) has been a relatively understudied area [128]. 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. [129] investigated rectangular channels in straight EAHEs, finding that this configuration enhanced heating and cooling performance, provided more stable channel wall temperatures, and reduced soil thermal disturbances compared to circular channel configurations. Jahanbin [130] 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. [131] 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 air and soil, respectively.

Numerous studies have investigated the influence of 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 [132]. 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 soil conditions, climate, and system design. Benrachi et al. [133] 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, [113] 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 airflow. However, Mihalakou et al. [134] observed a decrease in the temperature difference between the inlet and outlet air with increasing pipe diameter at constant airflow rate. In conclusion, the review of the literature revealed that while airflow velocity and pipe diameter play an important role in determining EAHE performance, the performance of the EAHE, optimal design parameters depend on a complex interaction of factors, including soil properties, climate conditions, and system configuration.

Multi-pipe Earth-Air Heat Exchangers (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 [135], 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 [136–139] and demonstrated that U-shaped configurations generally exhibit superior thermal performance compared to Z-shaped designs. These findings were corroborated by Qi et al. [140], who also observed improved thermal performance and airflow uniformity in L- and U-shaped configurations.

Despite these advantages, achieving optimal performance in multipipe EAHEs remains challenging. Recent studies [141] 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 [142], and the static pressure differential between the inlet and outlet of the final pipes can significantly affect airflow.

ly impact airflow.

Although U-shaped configurations have shown promise in mitigating these airflow disparities, neither U-shaped nor Z-shaped designs are without limitations. Experimental and CFD studies [143] 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 [144] have indicated that U-shaped configurations can exhibit lower outlet temperatures, potentially impacting overall system performance. This finding contradicts the results [145], 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 increased overall pressure drop in Z-shaped configurations. Uneven airflow distribution can have significant consequences, with [142] 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.

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The influence of installation depth and length has also been extensively investigated. Muehleisen et al. [146–148] proposed an optimal burial depth less than 5 m for EAHE, considering the trade-off between construction costs and energy efficiency.

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. Earth-to-Air Heat Exchangers (EAHEs) Integrating with Air-Source Heat Pumps (ASHPs)

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 energy efficiency in building heating and cooling systems. Studies such as those conducted by Congedo et al. [149], Guo et al. [150], Do et al. [151], Mahmoud et al. [152], and Cavazzini et al. [77] have shown promising results in various climatic conditions. Two primary integration methods have been explored: open-loop and closed-loop systems. Open-loop systems involve a direct interface between the ambient air and the ground. When ambient air through buried pipes, heat exchange occurs with the relatively stable ground temperature, preconditioning the air before entering the ASHP [153]. 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. The study aimed to assess the system's efficiency under real-world operating conditions and to quantify the benefits of coupling an EAHE with an ASHP. While ASHPs traditionally transfer heat between air and water for space heating and cooling, the 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 to replicate the system's behaviour. This model was calibrated and validated using a year's worth of operational data from the building. The analysis focused on two primary objectives: understanding the system's performance under real-world conditions and quantifying the advantages of integrating an EAHE. The results demonstrated that the integration of an EAHE significantly improved the system's performance. EAHE contributed approximately 50% of total heating demand during the winter, reducing the reliance on auxiliary heating sources. Furthermore, the EAHE ensured a relatively stable supply air temperature throughout the year, leading to more efficient operation of the heat pump. A detailed analysis of 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 the auxiliary heater.

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Closed-loop systems harness Earth's low-grade thermal energy by circulating air through an underground network of pipes [81,154]. Do et al. [151] 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 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.

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

4.1. Earth-to-Air Heat Exchangers (EAHEs) Integrating with Photovoltaic Systems

The integration of Earth-to-Air Heat Exchangers (EAHEs) with photovoltaic (PV) systems presents 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 studies conducted by Baglivo et al. [78], Kundu (et al. [155], Dokmak et al. [156], Yadav et al. [157], Hraibet et al. [158], and Zhao et al. [159]. 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 6).

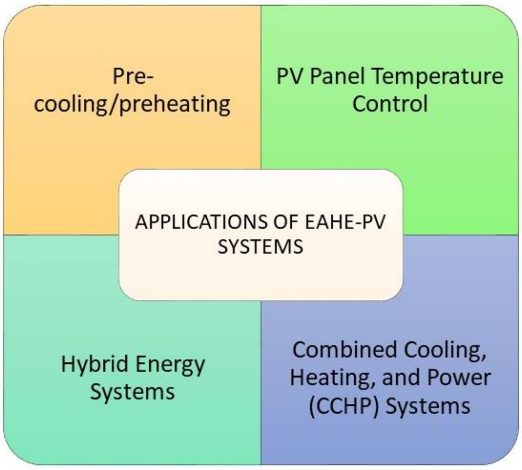

Figure 6. Applications of EAHE-PV systems.

A key advantage of integrating EAHEs with PV systems lies in their ability to pre-cool or preheat the supply air [160]. 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, minimising the energy required for space heating. This pre-conditioning process demonstrably improves the overall efficiency of the HVAC system, leading to a substantial decrease in energy consumption [78]. The hybrid system described in 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 the stable ground

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temperature for pre-conditioning outdoor air. This approach not only yields substantial energy savings, but also enhances a building's independence from external energy sources.

Building-Integrated Photovoltaics (BIPV) refers 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. This dual functionality offers several advantages, including improved aesthetics, reduced installation costs, and enhanced energy efficiency [161,162]. 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, the 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. Shahsavar 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 phase change material (PCM). The system was designed to meet 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 (a), depth and length of the EAHE (Di_{EAHE}, L_{EAHE}), with the aim of maximising thermal and electrical outputs. The optimal system configuration was determined to have dimensions of $L = 9.999$ m, $W = 5.0$ m, $D = 0.1$ m, $a = 1.73$ kg/s, $Di_{EAHE} = 0.5$ m and $L_{EAHE} = 91.147$ m. Increasing L, W, $\dot{m}_a$, L_{EAHE}, and Di_{EAHE}, while decreasing D, led to an increase in thermal output (Q). Similarly, increasing L, W, L_{EAHE}, and Di_{EAHE} and decreasing D and L_{EAHE} resulted in a higher electrical output (E). The optimal photovoltaic/thermal (HPT) system exhibited the highest electrical output in July and the lowest in December. During the cold months, it could provide heating power ranging from 17701.4 to 25295.7 kWh, while in the warm months it could deliver cooling power between 3092.7 and 6738.9 kWh. The optimized system could supply 26536.1 kWh of cooling load, 132693.3 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 [163]. For example, Dhaidan et al. [164] conducted a comprehensive review of the application of geothermal energy in agricultural solar greenhouses, highlighting the potential of EAHE to improve overall system performance.

Jakhar et al. [165] offers a comprehensive numerical investigation of the thermal performance of Earth-Air Heat Exchangers (EAHEs) integrated with Photovoltaic Thermal (PV/T) systems under varying climatic conditions. Research focusses on three distinct locations: Pilani, Ajmer (India), and Las Vegas (USA). A thermodynamic model was developed and validated against experimental data from the literature, demonstrating a high degree of correlation. The parametric analysis conducted revealed significant findings. Without cooling, the maximum cell temperature reached 54.3°C, 54.5°C, and 44.4°C for Pilani, Ajmer, and Las Vegas, respectively. However, with a cooling flow rate of 0.053 kg/s, these temperatures decreased to 43.4 ° C, 44.2 ° C and 35.6°C, respectively. The thermal power of the EAHE was notably enhanced when coupled with the PV/T collector, with increases ranging from 23.47 W·h–298.74 W·h, 71.18 W·h–315.93 W·h, and 41.43 W·h–270.75 W·h for Pilani, Ajmer, and Las Vegas, respectively.

Finally, Lopez-Pascual et al. [166] 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 Alcala 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

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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%.

4.2. Energy Systems Earth-to-Air Heat Exchangers (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 gained significant attention. Among these, solar chimney 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. In [167,168] presented experimental results from a solar greenhouse (SG) integrated with an EAHE and a photovoltaic system. In these studies, the 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 PV panel efficiency. For example, Yildiz et al. [169] reported a temperature reduction of approximately 8°C between the inlet and outlet of the EAHE, resulting in a 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. [170] 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 meet cooling loads while simultaneously generating a substantial amount of electricity. This research investigates the performance of a novel hybrid system designed to provide thermal comfort and electricity generation for residential buildings. The system integrates a solar chimney, photovoltaic panels, and an earth-air heat exchanger (SC-PV-EAHE). 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, known for their hot and arid climates. The EAHE system was modelled 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 meters and a length of 4.216 meters 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 output reaching 1060 Watts in Tehran and 781 Watts in Baghdad, respectively. The system exhibited high electrical efficiency, with values of 9.7% for Tehran and 8.9% for Baghdad. The generated electricity could be used to power the building's electrical systems and improve overall energy efficiency. These results not only validate the feasibility of such hybrid systems, but also highlight their potential to reduce reliance on convention-al 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 combined 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, the researchers 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 cooling performance and energy savings. Moreover, the system demonstrated substantial reductions in annual energy consumption and CO_2 emissions. Economic analysis revealed a relatively short payback period, highlighting the system's long-term economic viability.

Recent research by Li et al. [171] has explored the potential of integrating solar chimneys, earth air heat exchangers (EAHEs), and photovoltaic panels into a hybrid system for building applications. The study used MATLAB for the numerical modelling of the buried tubes, solar chimney, and the photovoltaic panels, while the building model was developed using the TRNSYS 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 the 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 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 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 supply air and outlet air temperature, with a negligible impact on the efficiency of the photovoltaic panels.

4.3. 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. In a study by Jang et al. [172] investigated a building-integrated Earth-Air Heat Exchanger (EAHE) retrofitted with a supplementary groundwater system in a cooling-dominated climate. This study investigates a Foundation-Integrated Water-based EAHE (FIWEAHE) system enhanced by circulating supplementary groundwater from a residential well. Experimental and numerical results demonstrate 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 24-26 ° C and winter temperatures of 20-21 ° C. The mean summer and winter COPs were 10.5 and 1.74, respectively. The study developed design relation curves to optimise pipe geometry and airflow velocity, providing valuable guidelines for the future design of the FIWEAHE system.

An integrated cooling system comprising an Earth Air Heat Exchanger (EAHE) and a water spray channel presents a promising avenue for achieving energy-efficient and sustainable building cooling. Research conducted by Ahmadi et al. [173] has shown that the 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 analyse 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

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system presents a viable alternative to conventional evaporative coolers or mechanical vapour 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. The performance is significantly influenced by ambient temperature, particularly during the summer months, which can lead to imbalances in power supply and demand [174,175]. 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 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 ambient air temperature and relative humidity. In hot and arid regions, direct evaporative cooling can offer economic advantages over electric refrigeration. Barakat et al. [176] 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.

In study [177] 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. The 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, investigating 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 meters and an approximate length of 300 meters is technically viable and offers a promising zero-water alternative to conventional water-cooling technologies. This study contributes to the growing body of research exploring 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. 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.

Shahsavar and Arıcı [178] investigated a novel hybrid system integrating 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 outdoor air before it enters the building 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 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

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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 synthesising the findings of recent studies, this review highlights the significant potential of EAHEs as a sustainable and energy efficient solution for building climate control. 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 tower, fogging system, water spray channel, 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 optimise the design of the system and predicting performance accurately. The complex interactions between heat transfer and mass transfer within EAHEs have been explored in detail, providing valuable insights for future research and development. Key findings from 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 optimising 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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