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Institute of Environmental Protection and Nature Conservation

Application of the Earth Air Heat Exchanger (EAHE) as sustainable technology for energy efficiency in building

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Sopron

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Application of the Earth Air Heat Exchanger (EAHE) as sustainable technology for energy efficiency in building

Written by in order to obtain Doctoral (PhD) degree:

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Nadjat KOUKI

“Nature is the source of all true knowledge. She has her own logic, her own laws; she has no effect without cause nor invention without necessity”

Leonardo da Vinci

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ABSTRACT

In accordance with the European Union's decarbonisation objectives, there is an increasing focus on the energy performance of non-residential buildings, especially educational institutions. Where it is essential for these facilities to maintain sufficient indoor air quality and thermal comfort while minimizing energy consumption, given that their heating, ventilation, and air conditioning systems (HVAC) generally function at high power levels, making efficiency improvements particularly impactful. This study evaluates the integration of an Earth-to-Air Heat Exchanger (EAHE) into a mechanical ventilation system for an existing school building. The real building located in southern Italy where the analysis was focused, equipped with fan-coil units and a centralized Air Handling Unit (AHU) and virtually simulated in the north central of Hungary. The proposed system integrates an EAHE upstream of the AHU in order to thermally precondition the outdoor, incoming humid air. Two climatic conditions are considered: a Mediterranean climate (Italy) and a Continental climate (Hungary). The hybrid EAHE-AHU configuration results in a significant reduction in the design thermal capacity required by the AHU coils. The reduction is quantified for different EAHE pipe lengths and diameters. The results show that the cooling coil design capacity can be reduced by up to 76% for Budapest and 46% for Naples. Under winter operating conditions, the heating coil design capacity reduction reaches 64% for Budapest and 72% for Naples.

LIST OF SYMBOLS AND ABBREVIATIONS

X	- Ground depth (m)
$T_{(x,t)}$	- Temperature of soil at a depth of 'x' meters and at a time of 't' hours (°C)
A	- Area (m^2)
ρ	- Density (kg/m^3)
α	- Thermal diffusivity (m^2/s)
Cp	- Air specific heat (J/kg K)
A_s	- Amplitude of annual surface temperature (°C)
ΔT	- Difference in temperature between Inlet and Outlet (°C)
v	- Air flow velocity (m/s)
L	- Length (m)
in	- Inlet
out	- Outlet
t	- time
Q	- Heat Transfer (kW)
ṁ	- Mass Flow Rate (kg/s)
T	- Temperature (°C)
D	- Diameter (m)
K	- Thermal Conductivity (W/m K)
η	- Efficiency
db	- Dry bulb
Ɛ	- Effectiveness
Φ	- Relative humidity (%)
Ꞷ	- Specific humidity (g/kg)
AC	- Air conditioner
ACHP	- Air cooled heat pump
AHU	- Air Handling Units
ASHRAE	- American Society of Heating, Refrigerating and Air Conditioning Engineers

ASHP	- Air source heat pump
CDD	- Cooling degree days
CCHP	- Combined Cooling, Heating, and Power systems
CFD	- Computational fluid dynamics
COP	- Coefficient of Performance
DH	- District heating
DHW	- Domestic hot water
EAHE	- Earth air heat exchanger
EER	- Energy efficiency ratio
EPBD	- Energy performance of buildings directive
EU	- European Union
GSHP	- Ground Source Heat Pump
HAGHE	- Horizontal air-ground heat exchanger
HDD	- Heating degree days
HEAHE	- Horizontal earth-to-air heat exchanger
HVAC	- Heating ventilation and air Conditioning
IAQ	- Indoor air quality
IEA	- International energy agency
MC	- Moisture content
NREAP	- National Renewable Energy Action Plan
nZEB	- Nearly zero-energy buildings
PCM	- Phase change material
PV	- Photovoltaic
PVC	- Polyvinyl chloride
RE	- Renewable energy
VEAHE	- Vertical earth-to-air heat exchanger
ZEB	- Zero energy buildings

CHAPTER 1

INTRODUCTION

1.1. Overview

This chapter provides a gateway to the current research and is structured as follows: Initially, it offers an overview of trends in building energy usage and its outlook in the near future. Subsequently, it describes the worldwide research issue. Finally, it highlights research gaps and justifies the contribution of this work to the field.

1.2. Research background

Reducing greenhouse gas emissions is a primary objective for every country. 2018/844 European Union's Directive mandates the establishment of a sustainable, decarbonized, secure and competitive energy system by 2050 [1]. Member states must outline a strategic plan with actions directed at achieving the long-term objective of greenhouse gas emissions reduction between 80–95% by 2050, relative to 1990 levels. This aims to guarantee a national building stock that is both highly energy-efficient and decarbonized, while also enabling the cost-effective conversion of present structures into almost zero-energy buildings [1]. Worldwide thermal? energy consumption is affected mainly by building sector contribution. In Europe, it accounts for around 36% of direct and indirect CO_2 emissions and 40% of final thermal energy usage [2]. In terms of habitat, the improvement of thermal regulation and the development of effective insulation materials has led to a significant reduction in energy consumption, decreasing from approximately 352 kWh/m²·yr in 1973 to around 190 kWh/m²·yr in 2010 in France [3]. This decline can be attributed to energy-saving initiatives, thermal regulations, and changes in consumer behaviour. Additionally, the residential energy per m² for space of the IEA selected countries (Canada, Austria, Hungary, Poland, Spain and other 18 countries) declined substantially from 2000 to 2018 [4].

To guarantee the thermal comfort and safety of room's indoor air quality (IAQ), a huge part of energy is applied, especially for heating, ventilation, and air conditioning (HVAC) systems. Traditional HVAC systems face several energetic and environmental challenges. Unsustainable and limited resources, degradation of the environment and large increment of energy demand are critical consequences of the use of conventional and traditional HVAC facilities. Furthermore, these systems can compromise indoor air quality, leading to potential health issues [5].

To meet these challenges, development of energy-efficient HVAC solutions is vital for achieving sustainability goals [6], [7]. These techniques not only help save on energy consumption and operating expenses, but they also improve air quality and indoor comfort while lowering environmental effect. Globally the priority now is to shift toward implanting the concept of sustainable development. Part of that can be done throughout the design of sustainable buildings.

The demands of cooling/heating energy and the thermal comfort requirements are rapidly increasing day by day due to global warming effect. To battel the climate change phenomenon, the European Union has adopted essential regulations, particularly the Energy Performance of Buildings Directive (EPBD) [8] and its subsequent recast [9]. This last directive proposes the theory of nearly Zero Energy Buildings (nZEBs), emphasizing that the zero or the very low energy needed should be sourced from renewables on – site or nearby. Giving that EU's space heating utilization reports 40% of the energy demand [10], expanding shallow geothermal systems deployment offers a prospective path for quickly lower the carbon footprint of the heating sector across Europe [11]. The best way to conserve energy in new housing while ensuring a high level of comfort for residents is to establish a foundational concept grounded in two primary criteria: the bioclimatic parameters of comfort and a suitable construction system.

In Hungary, the residential sector represents the largest proportion (32%) of the country's energy consumption [12] and around 65% is used for heating [13]. Passive heating/cooling solutions have experienced notable progress during the previous decade. Among them, ground heating/cooling, especially earth-to-air heat exchangers (EAHE) has been highlighted as sustainable attractive technological research subjects. EAHE featured with its ability in the enhancement of the indoor thermal comfort; significant contribution to the reduction of heating/cooling energy loads and the improvement of the urban environment. Aligned with the European Union's decarbonisation goals, growing attention is being paid to the energy performance of non-residential structures, with a particular emphasis on educational institutions. These facilities mush maintain adequate indoor air quality and thermal comfort while minimizing energy uses, as their HVAC systems generally function at high power levels.

Traditional research on the EAHE has mainly focused on its usage as standalone systems for pre-heating or pre-cooling a building through a comprehensive optimization of geometric and thermos-physical parameters to find the optimal system design depending on the location and the site of installation. However, when it comes to the integration of this system into standard mechanical ventilation systems such as Air Handling Unit (AHU), there is a remarkable lack of information, and the available literature remains limited. This knowledge gap is particularly evident in school buildings, which are featured by high ventilation rates, fixed occupancy schedules, strict indoor air quality requirements and significant peak ventilation loads. Consequently, school buildings serve as a significant yet insufficiently examined area for integration of EAHE and AHU, highlighting the importance of their potential effects on peak HVAC design loads and system sizing.

1.3. Problem description and justification of the research

Globally, a large portion of energy consumption is accounted for buildings, with HVAC systems responsible for up to 38-40% of this demand [14]. In school buildings, this contribution is notably pronounced due to increased mandatory external air ventilation rates, stringent indoor air quality (IAQ) standards, and specified occupancy schedules. According to ASHRAE Standard 62.1 and CEN EN 16798-1 [15], [16], educational buildings necessitate elevated fresh-air flow rates per occupant relative to several other building categories, making ventilation demands a pivotal consideration in HVAC system design. Consequently, traditional Air Handling Unit in schools must continuously condition large volumes of outdoor air to grantee building indoor comfort in climates with a huge seasonal fluctuation, leading to high peak heating and cooling demands and increased reliance on mechanical conditioning.

Even though, passive and renewable ventilation approaches have been extensively explored, the combination of EAHE system with standard AHU systems remains both limited theoretically and in practical school building applications.

Addressing this challenge in school buildings is a promising solution offered by the integration of an EAHE upstream of an AHU, as the system rely on the relatively stable soil temperature to pre-condition the outdoor air before it reach the AHU. This pre-conditioning changes the thermodynamics state of the inlet primary supply air, thereby this integration allows lowing the thermal loads imposed on AHU coils under design conditions, while upholding necessary ventilation and indoor air quality (IAQ) levels. Directly, this reduces the amount of design power needed by the conventional HVAC system, improve the efficiency of the system, and help to meet the environmental objectives and the energy performance targets and result in significant energy cost reduction. Although all these potential advantages, EAHE–AHU hybrid systems are not commonly implemented in Hungarian school buildings, where natural ventilation through window opening remains the predominant practice. Furthermore, limited studies have investigated the performance effects of these hybrid setups under continental climatic conditions, characterised by chilli winters, mild summers and important seasonal temperature amplitudes, as observed in Hungary. This research is therefore motivated by the need to evaluate the EAHE-AHU hybrid system within a school building environment, providing design-focused insights into its applicability, performance, and prospective contribution to sustainable and eco-friendly HVAC system design.

1.4. Research gap and the aim of the work

Experts evaluating the condition of our planet observe clear and undeniable signs that Earth is experiencing an increase in average annual temperature, in certain instances at an accelerated rate. It is widely accepted that human activities, especially the combustion of fossil fuels and the consequent accumulation of greenhouse gases in the environment, have played a significant role in this warming trend [17], [18]. The 21st century has experienced a significant rise in energy demand as illustrated in figure 1 and 2, affecting all sectors and critically impacting the HVAC field. [19]. Consequently, a radical "change of path" is highly required, beginning with the modification of our ideas on the sources of energy and rethinking of conventional air-conditioning strategies toward more sustainable solutions.

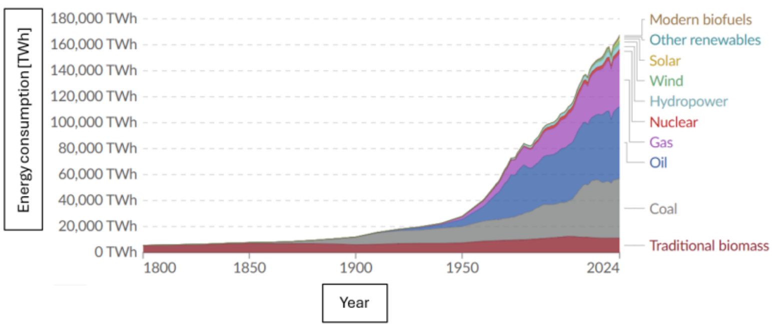


Figure 1. Global primary energy consumption (1800-2024) [20]

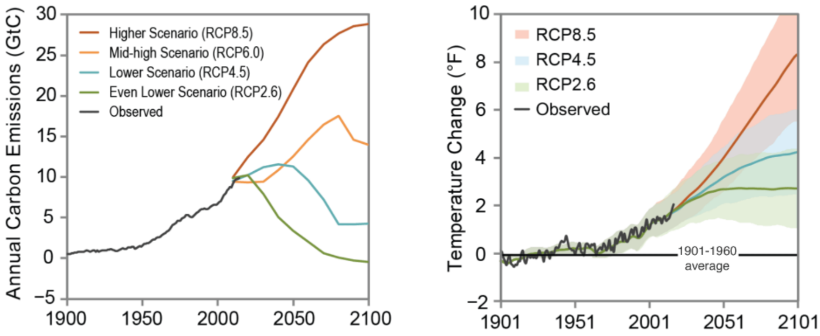


Figure 2. Projected annual global carbon emissions throughout the 21st century based on different possible energy policies and economic growth patterns and temperature increase relative to 1901-1960 [21]

European building performance and IAQ increasingly highlight the significance of controlled mechanical ventilation systems, including AHU, as essential facilitators of both energy efficiency and IAQ in non-residential structures. The European Union EPBD and associated standards acknowledge ventilation and air exchange as essential components of building performance and occupant well-being, particularly in airtight and low-energy structures where natural ventilation may be insufficient [22]. Moreover, many EU research programs such as the SINPHONIE project have highlighted the necessity of enhancing indoor air quality in schools rather than houses due to the large occupancy across member states and have proposed technical interventions, including mechanical ventilation, to mitigate pollutant levels and health impacts in classroom settings [23]. In contrast, to the author's knowledge, the current situation in Hungary shows that many school buildings rely predominantly on natural ventilation through window opening to control indoor air quality, without widespread implementation of centralized mechanical ventilation systems [24] and the state- of-art lacks a global efficiency assessment of a hybrid HVAC system with an EAHE located upstream of the AHU. Giving this gap then, encouraging the integration of AHU-based ventilation system with passive system like EAHE would align with EU policy trends, improve indoor environmental quality and support energy-efficient building operation in new and renovated Hungarian schools.

Within this context, the main objective of this study is to evaluate the effectiveness of integrating an EAHE upstream of an AHU in a school building, by quantifying the reduction in peak heating and cooling coil loads required to condition outdoor ventilation air on design days. This evaluation is conducted through a psychrometric-based analysis of the thermal and hygrometric transformations of air, comparing a baseline AHU system without EAHE to a hybrid EAHE–AHU configuration under different climatic conditions. To achieve this objective, the study pursues the following specific aims: (i) to model the pre-conditioning effect of the EAHE on outdoor air in terms of temperature, humidity ratio, relative humidity, and specific enthalpy; (ii) to quantify the impact of EAHE integration on the sensible and latent loads handled by the AHU heating and cooling coils under summer and winter design conditions; and (iii) to compare the peak heating and cooling coil capacity requirements of the AHU for baseline and EAHE-assisted configurations, highlighting the associated reduction in peak HVAC power demand relevant to coil sizing in school-building applications.

One of the key innovative aspects on this work lies in the implementation of the EAHE within educational settings, which present distinct operational characteristics compared to residential or commercial buildings, including high occupancy density, fixed schedules, and strict indoor air quality requirements. Additionally, the incorporation of shallow geothermal energy for managing ventilation air represents a sustainable approach that reduces dependence on conventional HVAC systems while maintaining occupant thermal comfort. Finally, by the decision to focus on the integration of EAHE into an existing AHU system rather than designing a new HVAC configuration, this research illustrates the feasibility of retrofitting operational school buildings with passive technologies, providing practical solutions for energy efficient renovation without major structural modifications.

1.5. Research assumption

This research claims that the proposed hybrid HVAC system connected to an EAHE has the potential to contribute positively to the reduction of energy requirements in non-residential buildings.

1.6. Research questions

In order to comprehend the operation of the hybrid HVAC system associated with EAHE placed before the AHU in different European climates, many study inquiries were formulated. These inquiries comprise:

1. How does the incorporation of EAHE upstream an AHU modify the thermal and hygrometric outdoor air properties under summer and winter design conditions in school building?
2. What is the impact of EAHE on the thermal loads handled by AHU coil when conditioning the ventilation outdoor air on design days?
3. What is the reduction achieved by the hybrid EAHE-AHU configuration in peak heating and cooling coil capacity requirements compared to a conventional baseline AHU in education building?
4. Can the integration of EAHE as passive pre-conditioning technology be a feasible and energy-efficient retrofit approach for educational facilities that need regulated mechanical ventilation?

1.7. Dissertation structure

This research is structured in five chapters as follows and illustrate in Figure 1:

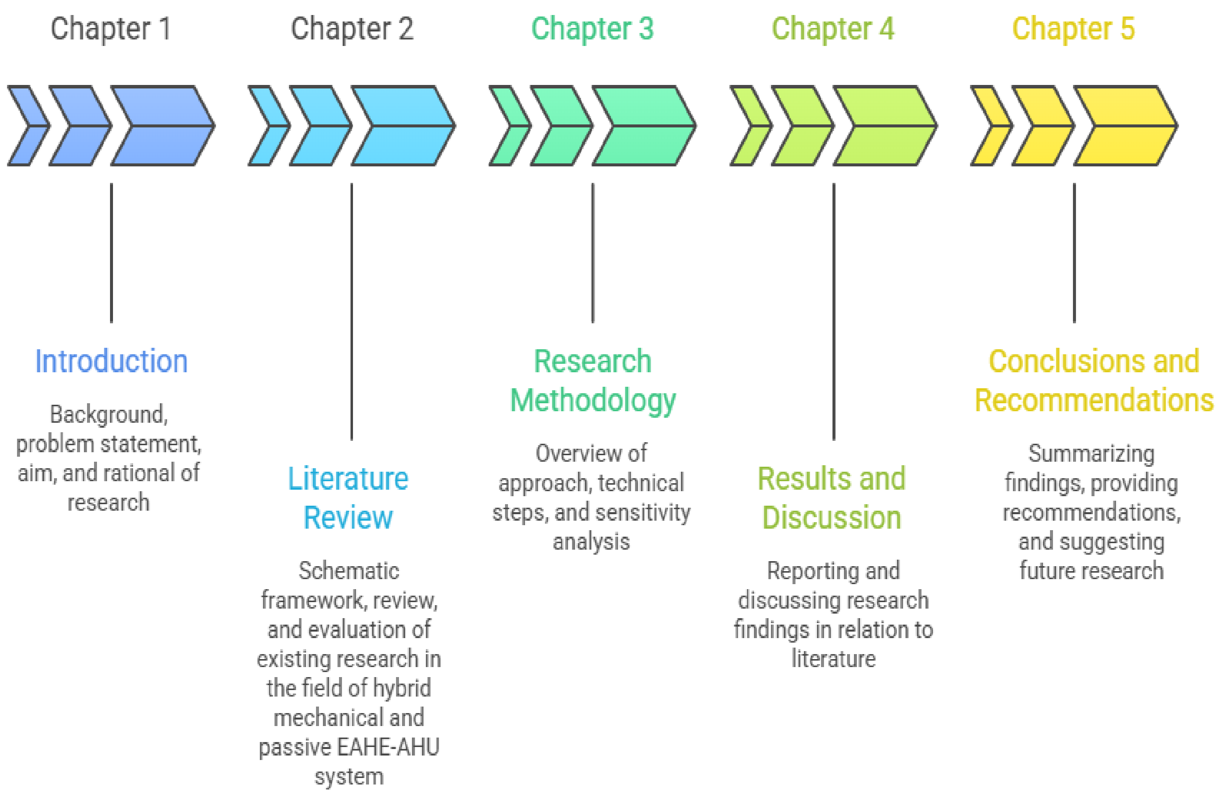


Figure 3. Structure of the dissertation

CHAPTER 2

LITERATURE REVIEW

2.1. Overview

This chapter explores existing research relevant to the application of EAHE, focusing on how this technology works to achieve building energy saving and what are its classification. The primary aim of this literature review is to establish the theoretical foundation for this study, identify gaps in the current knowledge, and position this research within the broader academic conversation.

The review covers recent studies using multiple numerical and parametric models to analyse deeply the influence of various design parameters including pipe material, pipe length, pipe diameter, the burial depth of the installation and the speed of the air passing in the EAHE ducts. While briefly addressing the influence of environmental parameters such as soil covering, soil moisture, soil density, and thermal conductivity due to a notable deficiency of research concerning these elements. Research on environmental parameters mostly depends on experimental soil investigations, which are more expensive than simulation studies, hence imposing limitations on these parameters.

2.2. Renewable energy and its importance

It is crucial to find the most ecologically and financially sound energy solutions to construct energy efficient homes. The focus these days is on trash recovery and recycling as a source of energy, as well as renewable energy (RE). The use of RE sources helps stabilize regional planning while also ensuring the reliability of our energy supply. They are safe for the environment since during energy production they don't produce any waste, pollutants or surplus emissions.

Renewable energy sources are becoming more significant in Hungary's energy system, yet their overall contribution at the national level remains relatively modest (Fig.4). According to recent assessments, the share of renewable energy in total energy consumption increased from 6.9% in 2005 to 16.2% in 2013, reaching 17.1% in 2023 [23], reflecting progress toward decarbonisation (Fig.5). Biomass is the dominant part of the Hungarian RES portfolio, which is the largest share of renewable energy use, primarily attributed to its widespread application in the heating sector and district heating systems.

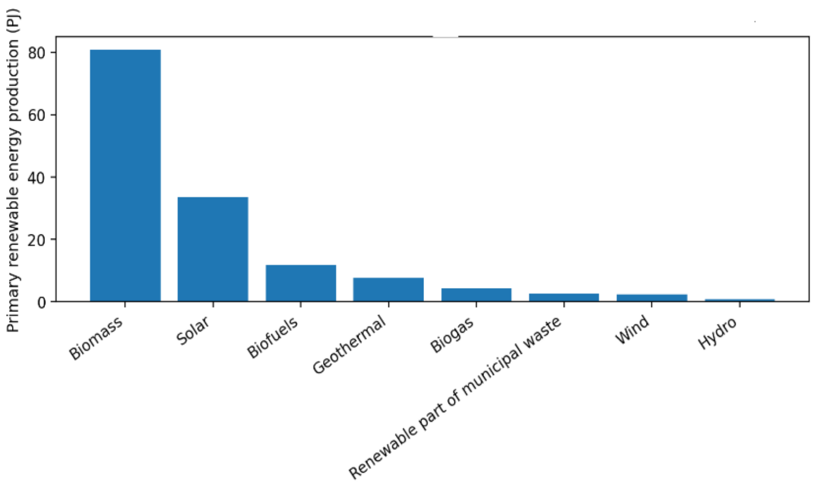


Figure 4. Hungary-primary renewable energy production by source (2024) [27]

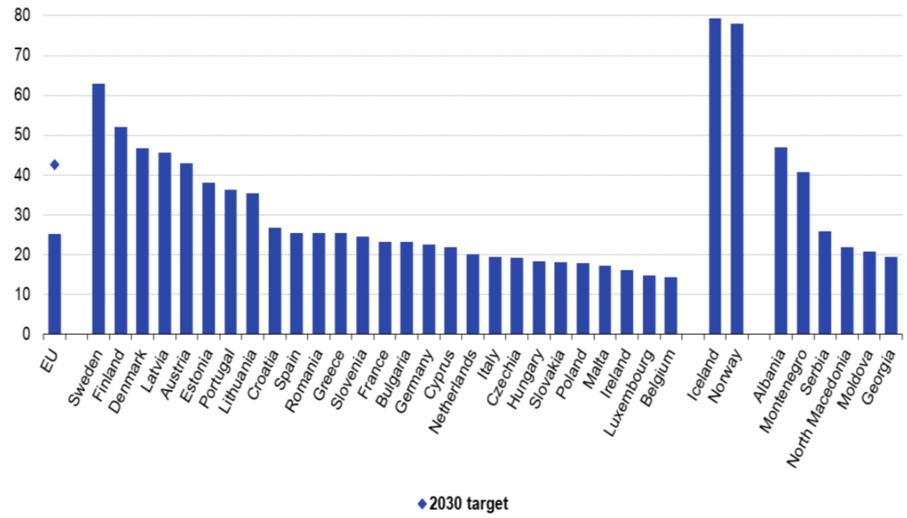


Figure 5. Share of renewable energy sources in total final energy consumption in the EU, 2024 [28].

Various studies [29], [30] highlight that solid biomass has traditionally been a fundamental component of Hungary’s renewable energy strategy, whereas other sources like wind and hydropower are limited due to geographical and regulatory challenges. In contrast, there has been significant development regarding solar photovoltaic energy which experienced rapid growth in recent years, emerging as the most dynamic renewable electricity technology; however, it has not yet displaced biomass as the dominant contributor in total renewable energy terms. This biomass-led RES structure is highlighting the importance of renewable heat in Hungary’s energy transition. The data published by MAVIR Zrt. [31] from the Hungarian transmission systems operator indicates that the installed capacity of solar power plants in Hungary surpassed 4,000 megawatts in 2022. Future projects have secured access to the transmission grid, totalling around 5,000 megawatts. Consequently, the installed PV capacity could potentially double in the coming years, aligning with Hungary's goal of achieving 6,000 megawatts of total installed solar capacity by 2030.

The wind farms in Hungary have a total capacity of approximately 330 megawatts. The authorization and construction of all wind power plants in Hungary occurred prior to 2016. Since that time, the establishment of new wind power plants has been hindered by stringent legislation, making the buildup of wind farms practically unfeasible [31].

Recent studies confirmed that hydropower constitutes a minor element of Hungary’s renewable energy mix, with restricted potential for growth. According to the latest Hungarian energy statistics, hydropower accounted for approximately 0.8 PJ in 2024 [26], representing less than 1% of Hungary’s primary renewable energy production, significantly trailing behind biomass and the swiftly expanding solar sector. This small contribution aligns with Hungary's low-head river conditions and the historically limited availability of large projects, where environmental and river-connectivity concerns (especially important in the broader Danube basin) have been pivotal in restricting new dam development and emphasizing ecological flow and habitat protection [32].Despite the favourable geological conditions of Hungary associated with the geothermal-rich Pannonian Basin and possesses extensive district heating (DH) networks; geothermal energy remains a “disproportionately weak” source, meeting only around

2% of heating requirements and utilized in a limited number of municipalities (approximately 30) [33]. Recent studies indicate that this underperformance is mainly driven by structural and infrastructural barriers rather than limited geothermal resources. A significant portion of Hungarian DH systems displays outdated and inefficient infrastructure, elevated design supply temperatures, and inadequate network insulation. These factors restrict compatibility with low- to medium-temperature geothermal heat and lead to increased distribution losses [34]. Additionally, geothermal projects carry high upfront capital requirements and operational challenges associated with corrosion and scaling due to highly mineralized geothermal fluids, increasing maintenance demands and diminishing economic viability [35]. Furthermore, the presence of regulated heat tariffs and the longstanding prominence of natural gas and biomass in the heating sector have diminished market incentives for the adoption of geothermal energy [36].

2.3. Historical background and development of geothermal energy

Through the study of volcanoes, hot springs, and various thermal phenomena, early humans deduced that certain regions of the Earth's interior are subjected to heat. Nevertheless, it was not until the 16^{th} and 17^{th} centuries, during the initial mining operations conducted several hundred meters below the ground, that individuals were able to infer the correlation between depth and the increase in temperature. Geothermal energy was utilized by American Paleo-Indians over 10,000 years ago in North America for the first time [37]. In the late 18^{th} century, the initial industrial utilization of geothermal energy took place in Pisa, Italy. Steam proceeding from natural vents or excavated holes was utilized to gather boric acid from the geothermal hot pools referred to as the Larderello fields.

Furthermore, in the early 20th century, Prince Piero Ginori Conti developed and investigated the electricity generation through the geothermal resources' application. On July 4,1904, he initiated the first experimental plant designed to showcase the potential of utilizing geothermal energy from a location near Larderello, Tuscany, Italy. The configuration featured a binary water cycle, producing pure steam to drive a piston engine connected to a 10 kW dynamo generator. The generator provided power to illuminate four interconnected light bulbs, each rated at 5 W [38]. The international oil crisis of 1973 provided significant encouragement for advancing geothermal energy development. Essentially, the majority of geothermal power plants were constructed during the 1970s and 1980s. The Pannonian Basin (Hungary, Serbia, Slovakia, Slovenia, Romania), Alpine and older structures of Southern Europe (Bulgaria, Romania, Turkey), various areas of the European Lowland (Germany, Poland), the Paris Basin in France and the Palaeogene systems of the Carpathians (Poland, Slovakia) indicate the primary geothermal fields presently being exploited [39].Considering the importance of this energy for both the environment and economic advancement, energy policy has become an essential tool for sustainable development. Following the end of the Second World War, geothermal energy has been recognized as an economically viable option compared to alternative energy sources. A number of nations take that into account. In 2010, geothermal energy had a total installed capacity of 10,897 MWe globally; this increased to 12,283 MWe in 2015 and reached 15,950 MWe by 2020 [40]. By 2025, the worldwide installed power capacity is projected to attain 19,361 MWe. By the year 2024, ten countries have been classified as having the highest number of set up geothermal power production facilities, as presented in Figure 6. It is illustrated that the United States is at the forefront with an installation of 2729 MWe, while Indonesia follows with 2533 MWe.

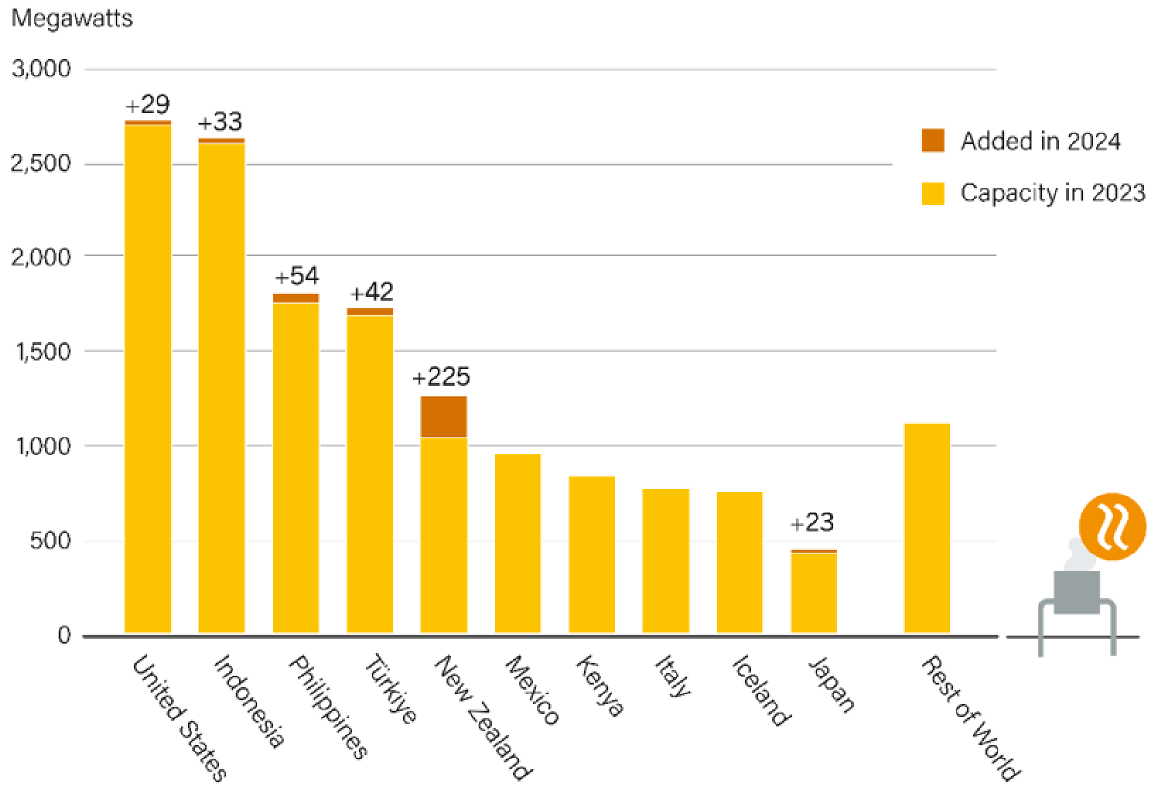


Figure 6. Geothermal power capacity and additions for the 10 top countries, 2024 [41].

Global geothermal heat utilisation has increased steadily in recent years, with growth largely concentrated in space-heating and district-heating applications. According to the global review by Lund and Tóth [42], the direct utilization of geothermal energy constitutes a significant and growing portion of geothermal implementation across the globe, especially for low- and medium-temperature thermal requirements. More recent analyses report that global geothermal direct-use output increased by approximately 30–35% between 2020 and 2023, and by 20% in 2024, reaching an estimated 245 TWh (882 PJ) [41], reflecting accelerated implementation in urban heating networks and public infrastructure. This expansion is driven primarily by countries with favourable geological conditions and established heat-distribution systems, most notably China and several European countries (Türkiye, Iceland), where geothermal district-heating projects are increasingly integrated into national decarbonisation strategies [43]. The leading nations for direct use in 2024, ranked from highest to lowest are illustrated in Figure 7.

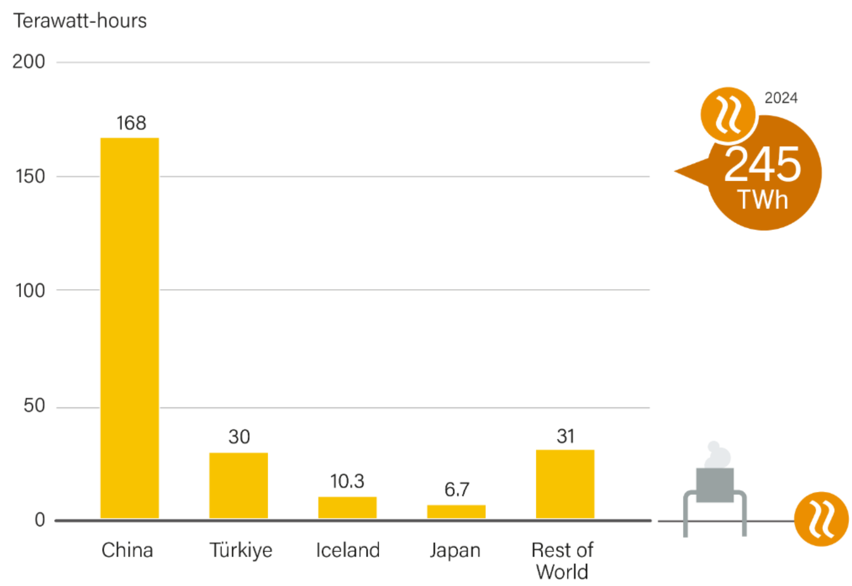


Figure 7. Geothermal Direct Use, Top 4 Countries and Rest of World, 2024 [41]

2.4. Geothermal potential and its applications in Hungary

Geothermal energy aligns with the worldwide demand for a transition to cleaner and more efficient energy sources. Therefore, it presents a persuasive avenue for sustainable development and economic growth. Geothermal resources are plentiful, consistently available, and have a low carbon footprint. The usage of geothermal energy is expected to rise significantly in various regions across the globe over the coming decades. The notion that geothermal energy could contribute to meeting the Paris Agreement's goal of limiting the rise in global temperatures to 2 °C or less is gaining increasing traction [44]. This energy source is of significant importance to the European Union. The €90 million grant allocated for geothermal technology research and development under the Horizon 2020 Framework Program from 2014 to 2018 was evident [45]. While under Horizon Europe (2021–2027), geothermal research and innovation has continued to receive targeted support through dedicated Cluster 5 calls including €10 million for “Solutions for more sustainable geothermal energy” (HORIZON-CL5-2021-D3-03-15) and €18 million for demonstrating high-temperature geothermal reservoirs as thermal energy storage (HORIZON-CL5-2022-D3-01-04) [46], [47] alongside large flagship grants such as PUSH-IT (EU contribution around €17.9 million, widely reported as an amount of €20 million Horizon Europe grant) [48], [49].Hungary is an excellent candidate for using geothermal energy as it has a great potential due to two factors. The initial aspect is the high heat flux to the surface, with this volume being around one and a half times the worldwide average [50], [51], [52]. The second is the existence of quality aquifers [53]. With the technology allowing a substantial proportion of its district heating systems, the nation is thought to have the largest geothermal potential in Europe. Currently the country has a target of raising this potential by maximizing geothermal energy output 15-20 times the current level [54]. The Royal Hungarian Geological Institute, established in 1869, and the Geophysical Institute, founded in 1907, significantly advanced geothermal research by gathering and organizing data.

During the period of industrialization in the mid-nineteenth century, the advancements in drilling technology created by Vilmos Zsigmondy and his nephew Béla Zsigmondy facilitated the extraction of thermal water from depths of 1000 m, leading to the popularization of bathing culture [55]. Furthermore, due to advancements in applied sciences like gravity measurements [56], Hungary has become a leading example in Europe for geothermal energy exploration and utilization by the early twentieth century. Particularly in the area of heat application [57]. Hungary presently achieves an annual geothermal output (including balneological applications) of 9.01 Petajoules (PJ), supported by an installed capacity of 1.02 Gigawatts thermal (GWt), with over 99% utilized for thermal energy purposes. Approximately 6.39 PJ is consumed for energy purposes. Geothermal energy contributes 6.5% to the nation's total heat production and is accessible at approximately 11 major geothermal utilisation sites (Szeged geothermal district heating system which is the largest and most advanced, Miskolc, Győr, Debrecen, Hódmezővásárhely, Szentes, Kecskemét, Veresegyház, Békéscsaba, Mosonmagyaróvár, Balneological clusters), primarily corresponding to urban district-heating systems and regional geothermal reservoirs rather than individual administrative cities [58]. The Hungarian national strategy outlines objectives aimed at enhancing the domestic utilization of geothermal energy by 20%, increasing from a baseline of 6.4 PJ to 8 PJ by 2026, and subsequently doubling the output to 12-13 PJ by 2030. By 2035, the aim is for geothermal energy to account for 25 to 30% of total heat production.

At present, Tura, Pest County, Hungary hosts a single geothermal power facility, boasting an installed capacity of 2.69 Megawatt electric (MWe) and 7.01 Megawatt thermal (MWth). According to the data at hand [58], the theoretical annual geothermal extraction potential in Hungary is estimated at 55.1–60.2 PJ yr^{-1}, while an additional 130.01 PJ corresponds to the estimated thermal energy stored in subsurface geological formations, representing a long-term underground heat storage potential. A significant element contributing to the advantageous geothermal conditions in Hungary is the Carpathian Basin, which consists of a sandy clay sedimentary series along with deeper layers of limestones and dolomites. The Carpathian Basin has a long-standing reputation, spanning thousands of years, as a region abundant in medicinal and thermal waters. Hungary is known with a significant amount of geothermal heat flow vary between 50 mW/m^2 and 130 mW/m^2 with a mean of 90-100 mW/m^2 and a geothermal gradient of about 45 °C/km [52], [59]. The Middle Miocene lithosphere extension account for this strong heat flux. Low readings are found in recharge zones of karstic flow systems, whereas the highest levels are found in the southern and eastern part of the country. Hungary significantly contributed to scientific research on medicinal thermal waters, highlighted by the first International Congress of Balneology that took place in Budapest in 1936. Unsurprisingly, Budapest is famous for its thermal water use, especially bathing and balneology which have a long historical record, had been used in the Roman Empire and later in the medieval Hungarian Kingdom. From there Budapest was named the City of Spas. The first geothermal well in Budapest was completed in 1866 [60]. In addition to deep geothermal energy, boosting shallow geothermal energy can contribute significantly to enhance the share of geothermal energy in the total heat production by 30%. The utilisation of shallow geothermal energy for space heating in Hungary is a more recent development and is far from reaching its full potential [10]. First Ground Source Heat Pumps (GSHPs) were installed in the 1990s [10]. The planning of shallow geothermal systems has been based on either the Hungarian MSZ EN 15450:2008 standard or the more detailed German VDI 4640 standard. However, proper system sizing and long-term sustainability over multi-decadal operation may not be fully ensured when relying solely on MSZ EN 15450:2008 or VDI 4640, as these standards do not explicitly account for location-specific thermogeological conditions, field-scale borehole thermal interference, or groundwater-driven advective heat transport. Addressing this methodological gap requires detailed and site-specific modelling approaches, such as the infinite borehole field model proposed by Korhonen et al. [10].

When considered relative to population size national territory, Hungary displays a comparatively strong level of thermal energy utilisation. Accordingly, the country demonstrates a diversified application of such renewable energy sources, which are summarised in Table 1. For reference, 1 terajoule (TJ) corresponds to 277.78 megawatt-hours (MWh).

The first and the earliest known application of the Hungarian thermal water is the balneology use. Globally recognized spas are located in Budapest, Hajdúszoboszló, Hévíz, Bük, Sárvár, Harkány and Zalakaros in addition to other places. A collection of 214 thermal wells and 120 natural springs provide water for recreational and medicinal uses [61].

District and space heating with geothermal energy started in proximity to balneological facilities. The initial examples are many residential buildings and the Budapest Zoo during the interwar period. All through the late 1950s, district heating initiatives started across Southeast Hungary, including Szentes, Hódmezővásárhely, Szeged and Makó. Natural gas is available always in these urban heating plants in case of malfunctions and to meet the peak demand. Hungary hosts the second largest geothermal district heating system in Europe after Iceland and the largest in the EU placed in Szeged. At the present more than 50.000 flats/apartments are heat up by thermal/geothermal water largely concentrated in Szeged and Győr [62]. This geothermal heat generation application can help in dropping Hungary's reliance on imports, and in raising renewable energy sources share in the primary energy mix. For instance, one of the eldest geothermal district heating systems in Hódmezővásárhely reduces CO_2 emissions by 4,680 tons yearly and conserves 4.5 million cubic meters of gas. Noting that 3500 HUF per GJ determined to be average consumer price for district heat in this town [63].

Over 50 cases of animal gardening are heated by geothermal water at pigs, turkey and chicken farms. Furthermore, low temperature released waters provide a source for fishponds in nearby of Győr and Szentes [64].

Geothermal application for agricultural purposes is important in Hungary. The utilization of geothermal energy in Hungary is predominantly focused on agricultural applications. Greenhouses exceeding 500,000 m^2, along with plastic tunnels and soil heating, are powered by thermal water [64]. Well controlled and constructed advanced systems exist, wherein many geothermal wells provide a sequential cascade of sub-systems: greenhouses, plastic tunnels, and soil heating are interconnected (e.g. Szentes). In other cases, a single well supplies warm water straight to greenhouses. Its discharge, which remains rather hot, results in low efficiency and occasionally leads to environmental issues.

Table 1. Geothermal heat production distribution in Hungary [65].

Areas of application	**Installed capacity [MW]**	**Maximum heat output [TJ/year]**	**Proportion [%]**
Balneology (Spa)	352	3912.03	38.9
Greenhouse heating	271	3024.12	29.9
District heating	153.56	1700.26	17
Geothermal heat pumping	42	695	4.6
Individual space heating	33.02	326.05	3.6
Agricultural drying	25	297.13	2.8
Industrial heat production	19	220.62	2.1
Fish and livestock breeding	10	92.85	1.1
Total	905.58	10,268.06	100

2.5. Geo-energy policy and regulation at the national level in Hungary

Throughout its history, Hungary relied on energy imports to satisfy a substantial share of its energy demand with energy import dependency remains at levels of around 49% of its total energy needs in 2024 [65]. In parallel, multiple recent assessments note a marked contraction in domestic energy demand: sectoral analyses and market reporting describe a rapid decline in total energy consumption after 2021 (from about 1,154.6 PJ in 2021 to 1,013 PJ in 2024), corresponding to an average reduction of approximately 4% per year over 2021–2024 [66]. Around 83% of Hungary's hydrocarbons, along with approximately 20 billion m^3 per year of natural gas, are primarily sourced from Russia. This poses an important threat to the nation's energy stability, particularly within the heating sector [67]. Consequently, Hungary has significantly enhanced its geothermal policy framework. It amended its legislation related to the research, extraction and utilisation of geothermal energy. This government decree took effect on 1 March 2023 [68]. Hungary's National Energy Strategy for 2011-2030 examines how the nation can optimize its resource utilization, with a strong focus on enhancing the share of renewables as a key component. According to the Ministry of Energy government's estimation, geothermal energy can substitute up to 1-1.5 billion cubic metres of natural gas by 2030, significantly reducing Hungary's import dependency [68]. Hungary's National Renewable Energy Action Plan (NREAP) target was 14,65% Renewable Energy Sources (RES) by 2020 with geothermal given a 17% share of the total RES goal. By 2020, geothermal target divided as the following: GSHP with 5,99 PJ, direct use around 16,43 PJ and 57 MWe for power production. However, these targets were not fully achieved. Reported geothermal heat utilisation in 2019 amounted to approximately 10.7 PJ yr^{-1}, substantially below the National Renewable Energy Action Plan (NREAP) target for direct use, while GSHP deployment remained limited and insufficiently documented to support the targeted contribution [67]. The shortfall between the geothermal targets set in the NREAP and the levels of deployment actually achieved by 2020 provided a key policy rationale for the 2023 amendment of Hungary's geothermal legislation, which aimed to remove regulatory and financial barriers and to accelerate geothermal exploration and utilisation.

The government has frequently articulated its firm commitment to promoting geothermal energy in Hungary. The EU2030 targets, which encompass the 32% RES proportion at the EU level, are also being considered. Under the National Geothermal Strategy, which seeks to enhance energy sovereignty, boost emission-free energy production, and maintain cheap energy prices, Hungary intends to double its domestic geothermal energy utilization by 2030. To create a stable funding environment and decrease financial risks, the approach involves government support of about 165 billion Hungarian forints (418 million euros). Furthermore, Hungary's National Geothermal Strategy aims to increase domestic geothermal energy use for energetic (mainly heat) purposes from a baseline of 6.4 PJ by approximately 20% to about 8 PJ by 2026, with a longer-term objective of expanding geothermal use to 12–13 PJ by around 2030. During the strategy's duration, the proportion of geothermal energy in overall heat production may rise from 6.5% to between 25 - 30% [69].

2.6. Classification and application of geothermal energy

Geothermal energy is often classified as shallow and deep geothermal, especially in practical applications and engineering contexts. The geological background is one of a high temperature basin and not volcanic, so the potential is limited and mainly focuses on heat production.

2.6.1. Deep geothermal

The exploitation of deep geothermal energy has attracted significant interest in the energy sector because of its substantial reserves. Deep geothermal energy exploitation is a type of underground engineering. It is a complex process that includes geological survey, generating plant installation, drilling, reservoir establishing, fluid circulation, operation, energy utilization. Deep geothermal energy is the heat taken from deep below, usually at depths more than 500 m, when the Earth's geothermal gradient causes notably higher temperatures. Among the several uses for this heat are industrial operations, building heating (Direct or District heating) and power generation. This type of geothermal has significant benefits. Deep geothermal resources are widely distributed, making it a potential energy source for many regions. It offers baseload power and heat from a dependable, 24/7 energy source and it has a relatively small surface footprint and can be a low-carbon energy source.

2.6.2. Shallow geothermal

Shallow geothermal, it named also near-surface geothermal referred to the low-temperature thermal energy that is held in the upper layers of the Earth's crust. This type of geothermal energy often occurs and exploits the relatively constant temperatures (often between 10–18 °C in temperate regions) found at depths that are less than 400–500 m. To heat and cool, shallow geothermal systems employ low-grade heat from the ground primarily through ground-source heat pumps or air-to-earth exchangers (EAHE), in contrast to deep geothermal systems that rely on high-temperature geothermal reservoirs. Furthermore, close to surface it mainly affected by solar radiation, air temperature, and seasonal fluctuations. Due to its availability, scalability, and environmental benefits, shallow geothermal energy plays a crucial role in achieving decarbonized building energy systems.

Table 2. Types of geothermal energy

Geothermal type	Depth	Temperature	Primary application
Deep	> 500 m (up to 5 km or more)	~ 60°C - 300	Power production, industrial heat and large-scale heating purposes.
Shallow	< 400-500 m	~10-50 °C	Heating/cooling building via heat pumps or EAHE

2.7. Geothermal energy in Building

Sustainable and renewable option like geothermal energy has gained more attention in the development of building application by improving the thermal comfort, decreasing dependence on fossil fuels and minimizing operational energy expenses. Shallow geothermal systems, which employ the fairly consistent temperature of the ground's top layers (2 - 10 m below the surface), are becoming more popular for cooling/heating and domestic hot water generation. These systems include Ground Source Heat Pump (GSHP) and EAHE [70]. Both technologies utilize the ground as a natural heat source in winter, while in the summer, they are used as a heat sink.

Geothermal energy applications can be seen in commercial, residential and educational facilities. Numerous case studies in Europe illustrate the efficacy of shallow geo-systems in attaining near-zero-energy or low-carbon construction objectives. EAHE is especially advantageous for educational and public facilities that need continuous ventilation [71].

Furthermore, geothermal systems have the potential to be integrated with other renewable technologies as solar thermal collectors or photovoltaic panels to develop hybrid renewable energy systems [72], [73]. These integrated systems enhance the stability of building energy demand, optimize the utilization of local energy resources and bolster overall system resilience.

2.8. Heating and cooling demand in Hungary

The most obvious impact of climate change in Hungary is the increase in extremes associated with high temperatures. Changes in the climate and advancements in building technology have significantly influenced Hungary's requirements for heating and cooling. Historically, Hungary's energy consumption was dominated by heating needs. The duration of the heating phase is 183 days in Hungary [74], and it constitutes about 71% of the overall final energy consumption in households [75]. Solid fuels and gas are more prevalent heating sources (particularly in rural ongoing energy crisis, natural gas and electricity use constitute the primary sources of higher expenses for consumers). However, in urban areas a clear shift towards heating requirements reduction and an increased demand for cooling due to the higher frequency of the heat waves are indicated in recent data. Rising temperatures could lead to shorter heating seasons and milder cold months, potentially reducing heating energy demand.

That means the length of the temperature-based heating period decreased substantially, while the length of the cooling period increased as a consequence of overall regional warming.

The heating degree day (HDD) is an indicator of the energy consumption for heating of buildings, which depends only on the weather. The temperature value, represented in °Cday, indicates the amount of energy necessary to achieve a specific indoor temperature on a particular day. This calculation considers the daily minimum, maximum, and mean temperatures relative to a defined base temperature of 15.5°C [76]. it’s worth is independent of the insulation quality of the structures, economic metrics, or the nature of energy sources. In essence, as the weather becomes colder and the air temperature moves further away from the baseline of 15.5 degrees Celsius, there is an increased demand for energy to maintain a comfortable indoor environment, resulting in a higher value of heating degree days. Furthermore, the cooling degree day (CDD) is calculated in a manner like the derivation of the heating degree day. Consequently, as the weather becomes warmer and air temperatures rise above the baseline of 22°C, an increased amount of energy is required to maintain a comfortable indoor climate [76]. From 1901 to 2019 a comprehensive meteorological data examination held in Budapest indicates a notable increment in CDD by approximately 79 °C.day alongside a decline in HDD by about 314 °C.day. This trend suggests a reduction in the heating season duration and an extension of the cooling season, characterized by greater intensity [77]. Additionally, trends of modifications in occupancy and buildings renovations significantly influence the energy consumption of district heating according to findings from Miskolc. A comparative analysis between 2015 and 2022, utilizing high-resolution consumption data, indicated a significant reduction in heating demand subsequent to insulation enhancements and modernization initiatives [78]. Increment temperatures in Hungary are leading to expectation of high demand of cooling technologies solutions and presenting challenges in the design of energy-efficient and environmentally sustainable buildings. Therefore, the HVAC system necessity of this trend highlights the need for strategies as improved passive cooling, enhanced insulation of buildings and Renewable heating systems adoption like Earth Air Heat Exchanger system.

2.9. Thermal comfort in buildings

Thermal comfort is stated by ISO 7730 and ASHRAE Standard 55 as the “the condition of mind that reflects satisfaction with the thermal environment” [79]. However, in educational environments, thermal comfort exceeds occupant satisfaction; it plays a vital role in influencing cognitive performance and learning outcomes. The experience of thermal comfort is mostly subjective and will differ across individuals. Variations in metabolism and outlooks result in notable variances from person to another. Concerning occupants’ thermal comfort as determined by temperature, humidity, air movement, and related environmental factors, the research therefore account for all these factors. Typically, these characteristics complicate the identification of a singular thermal environment that will be acceptable to everybody. A thermal climate is generally considered satisfactory to a minimum of 80% of the inhabitants in an interior area. Although general standards like ISO 7730 and ASHRAE 55 establish a foundational framework, recent studies highlight that children and students exhibit greater sensitivity to thermal variations compared to adults, typically preferring lower indoor temperatures. That is attributable to their higher metabolic rates and distinct surface-area-to-mass ratios [80]. In Mediterranean climates, field studies show that students frequently experience thermal sensation in ways that differ from the Predicted Mean Vote (PMV) model. They often tolerate higher temperatures while simultaneously reporting a notable decline in perceived air quality as temperatures increase, irrespective of CO_2 levels [81]. Field research in continental climates similarly reveal inconsistencies between occupants' thermal perception and the Predicted Mean Vote (PMV) model, although with distinct adaption patterns relative to Mediterranean locations. Further, it indicates that thermal sensation votes tend to vary with external temperature, hence supporting adaptive comfort theory over static PMV predictions [77], [82]. Critically for educational settings, thermal comfort is fundamentally associated with learning efficiency. Recent research indicates that moderately raised temperatures (exceeding 25–27°C) result in heightened mental load and a quantifiable decrease in cognitive task performance, even when students can modify their attire to maintain 'thermal neutrality' [83], [84]. This highlights the significance of the EAHE–AHU system's capacity to mitigate peak summer loads, as preventing even minor overheating is essential for sustaining student focus and academic performance.

The thermal control systems, namely HVAC, aboard an accommodation vessel must be engineered to regulate indoor thermal external variables within acceptable ranges to ensure occupant comfort. In the context of naturally ventilated buildings, Humphreys and Nicol [85] formulated a correlation between outdoor (external) average temperature (T_o) and temperature of comfort (T_c). This equation is presented as follows:

$$T_c = 13.2 + 0.534\,T_o \quad (1)$$

Their findings indicate that this relationship remains notably consistent when comparing with Humphreys' data [86] and de Dear's [86] ASHRAE database [87].

2.10. Earth-Air-Heat Exchanger technology

2.10.1. Historical background of EAHE

Investigation into Earth Air Heat Exchangers as heat source/sink was known in ancient times, in about 3000 B.C., Iranian architects (Qanāt systems) used underground air tunnels and wind towers for passive cooling [88], [89]. Due to the contact with cooler underground surfaces these conduits cooled the incoming air resulting in early versions of EAHE technology. The Romans used the same approach, integrating similar earth-duct cooling techniques in their bathhouses. EAHE have been utilized in agricultural structures (animal housing) and horticultural establishments (greenhouses) in the United States for several decades. It seems to have commenced following the peak oil event in 1979, as specialists explored its possibilities for energy savings and conservation. However, it discontinued temporarily following the counter-shock of 1985 [90], only to resurge in the mid-1990s when investigations focused on the thermal behaviour of EAHEs, issues of their performance, and their integration into buildings as an air pre-conditioning system. During this period, the implementation of these systems in India, Denmark, Austria and Germany has become rather commonplace and is gradually being implemented in North America. Then from 1995-2000s, there where the beginning appearance of the integration of hybrid designs EAHE alongside solar chimney system in arid regions, likely originating in the Persian Empire [91]. This Era also saw the research development on the categorization of such system into two: open loop and close loop systems [92]. Today, EAHEs are widely investigated and employed in residential and commercial buildings, as well as in farming, greenhouse temperature management, and industrial operations.

Table 3. Timeline summary of EAHE development

Era	EAHE situation
~ 3000 B.C	Utilization of Roman bath ducts and Qanāts system in the Middle East, which are the earliest/ origin version of EAHE technology.
1979s-1985s	EAHE was re-examined during periods of energy crises, followed by a resurgence in the mid-90s.
1995s-2000s	Appearance of hybrid designs and the development of open- and closed-loop systems.
2001s-present	Worldwide studies of models and experiments in building science and climate control; implementation across many industries; global integration in several sectors large and small scale.

2.10.2. Description and operating principle of EAHE

This type of exchangers is called earth tubes (also known as earth cooling tubes or earth warming tubes) in Europe or earth–air heat exchangers (EAHE or EAHX) in North America. An EAHE serves as a passive method for preheating ventilation and process air during winter and precooling it in summer. It processes outdoor air by exchanging thermal energy with the surrounding ground. The primary benefits of the EAHE system are its simplicity, significant cooling and pre-heating capabilities, low operating and maintenance expenses, conservation of fossil fuels, and reduction of associated emissions [93]. The heat exchange occur within this system can be affected by number of parameters, including surface cover; type of soil; compaction and moister; layout and materiel of the pipe; pipe size such as diameter and length; depth of pipe installation under the ground and the velocity of the air. Further, other seasonal factors like precipitation; snowfall; surface wind velocity; temperature and solar radiation will influence soil temperatures, which will affect the performance of an earth-to-air heat exchanger.

EAHE system design must be considering these characteristics to achieve the necessary temperature differential and heat transfer rate efficiently and economically. These parameters will be described in this chapter.

Based on climatic conditions, season day and time, the external air experiences significant fluctuations in humidity and temperature. Conversely, the ground, few meters under its surface, has a little temperature fluctuation owing to its significant thermal inertia. The Earth Air Heat Exchanger, named in the past as Canadian well or Provençal well, utilizes this significant inertia by establishing thermal contact between the outside air and the ground. Firstly, the main objective is to prepare the ventilation air of buildings through thermal and hygrometric pre-conditioning. Additionally, it can prevent winter icing of the exchanger on stale air when it is linked with it upstream.

Concretely, the fundamental concept of the EAHE is that one or several pipes (tunnels or ducts) are buried in the soil at 3-4 m near or directly under the building to be ventilated. One end of the pipe system (the inlet) acts as the entrance for outdoor ambient air, whilst the other end of the pipe system (the outlet) releases air to the interior of a building. Ambient air is driven by a fan into the pipe inlet, where it traverses the pipe, exchanging heat with the walls of pipe that are in contact with the surrounding subterranean environment. In this way, soil is either absorbing (pre-cool) or adding (pre-heat) heat to the system by convection with the tunnel air or conduction through the pipe wall, tempering the air as it flows through the pipe (Figure 8), subsequently reducing the cooling/heating load on the HVAC system [94]. This system consumes very little electricity; so, it is almost passive.

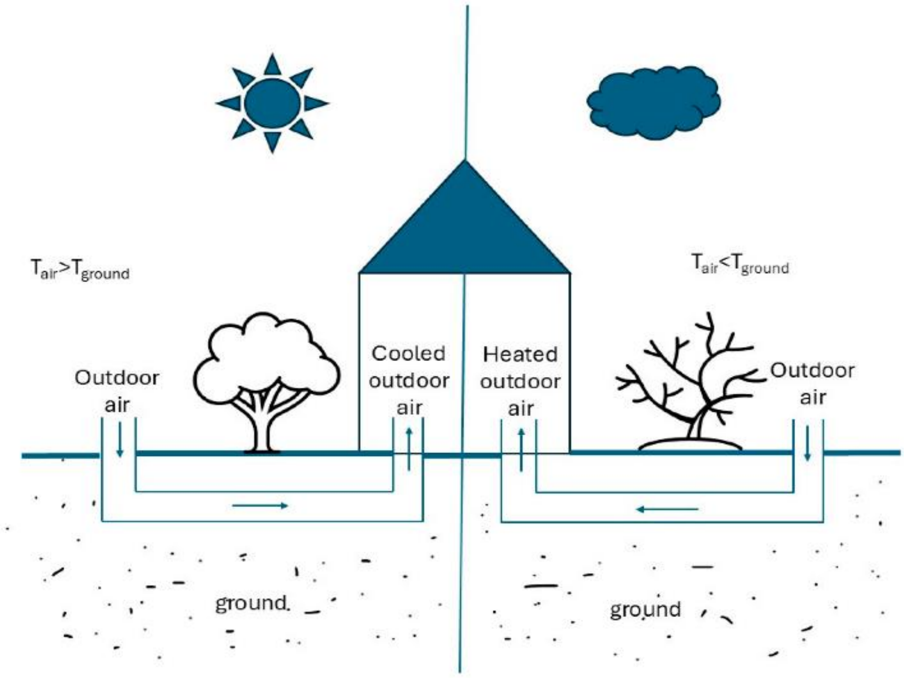


Figure 8. EAHE system for pre-heating and pre-cooling the outdoor air in winter and summer seasons

This particular equipment may not be appropriate for every type of building. Indeed, the construction process necessitates the excavation of relatively deep trenches, ranging from one to several meters, and demands a considerable amount of ground space. It appears to be more appropriate for structures situated in open spaces, such as suburban districts or business areas, rather than for those found in densely populated urban environments. Buildings of various dimensions can incorporate them, ranging from single-family homes to multi-unit residences and commercial office spaces [95]. From a technical and economic perspective, it is advantageous to install the piping system during the execution of the structural work, rather than after the building has been commissioned.

2.10.2.1. Pipe role in EAHE

The pipe serves as a medium for thermal exchange, connecting the fluid (air) flowing through it with the backfill or adjacent soil. The ideal pipe would be one that is long-lasting, simple to set up, strong, versatile, and affordable; it would also be able to resist wear and tear, leaks and damage. Additionally, its substance should require high thermal conductivity to improve efficiency in heat transmission in both directions [96]. EAHE systems rely only on blowers to move air through pipes, transferring heat from the air to the land. When compared to more traditional forms of air conditioning, this system is both practical and cost-effective. Generally, pipes are often fabricated from materials exhibiting strong heat conductivity, corrosion resistance, and durability.

2.10.3. Geothermal role in EAHE

Geothermal energy presents a distinctive benefit. The soil temperature at a designated depth, suitable for the installation of an EAHE, displays a consistent stability across the seasons [97]. Soil temperature fluctuates daily and seasonally, mostly driven by solar radiation and air temperature. During daytime, terrestrial surfaces absorb solar energy, resulting in temperature increment. A portion of this thermal energy is re-emitted into the atmosphere by evaporation and convection, while the remainder is sent to the subsurface. The temporal lag in temperatures between the subsurface and surface results in year-round temperature stability in the subsoil [98]. The variations in ground temperature are less pronounced than the seasonal variations in external air temperature. Furthermore, to mitigate these variations that may impact the functioning of geothermal systems, regulatory measures are used that concentrate on HVAC systems rather than being tailored specifically to geothermal systems. Moreover, the ground temperature at greater depths almost matches the annual mean temperature of the air. Consequently, winter temperatures are raised compared to those at the Earth's surface, but summer temperatures are diminished relative to surface temperatures [99]. This accounts for the soil's double function as a source and heat sink even though it functions both as a cooling and heating medium [100].

2.10.4. Classification of EAHE

The significant advancements of EAHE lead to the development of various system types, distinguished by differences in control strategies, configurations, and materials. This technology is generally classified according to pipe orientation (horizontal or vertical), pipe configuration (single-pipe, multi-pipe, or parallel arrangements), system operation mode, airflow configuration, and design characteristics such as pipe material, diameter, and length. In addition, recent advancements involve improved control techniques and incorporation of EAHE systems with various renewable energy sources and automated control systems. Such classification aids in comprehending the development and optimization of EAHE systems and it is presented in Figure 10.

Recent research trends show a strengthening interest in using EAHE in hybrid configurations. However, the system is also identified as a sustainable solution that can operate effectively as a standalone unit. Thus, on the objective of improving the system overall energy efficiency and performance, many studies have focused on combining it with other passive and active building strategies.

The main categories of the EAHE classification based on scientific literature are:

2.10.4.1. Classification based on airflow configuration

- **Open- loop system:** Where, the outdoor ambient air (fresh air) is passing through the EAHE pipes for preheating or pre-cooling (Figure 9 (a)). While the air is drawn into the buried pipes, it transfers thermal energy with the adjacent soil before it enters the room. The result is presented in the absence of recirculation in this loop because the air passes only once through the pipe system [101].
- **Closed- loop system:** In this loop, recirculated interior air is used instead of fresh air (Figure 9(b)). Air is extracted from the inside of the building, sent via underground pipes for heat exchange with the surrounding soil, and then returned to the building. There is no introduction of fresh outdoor air in this kind of loops [102].

Based on the available literature, due to the ability to support fresh air, the open-loop system is frequently preferred over the closed-loop system [103].

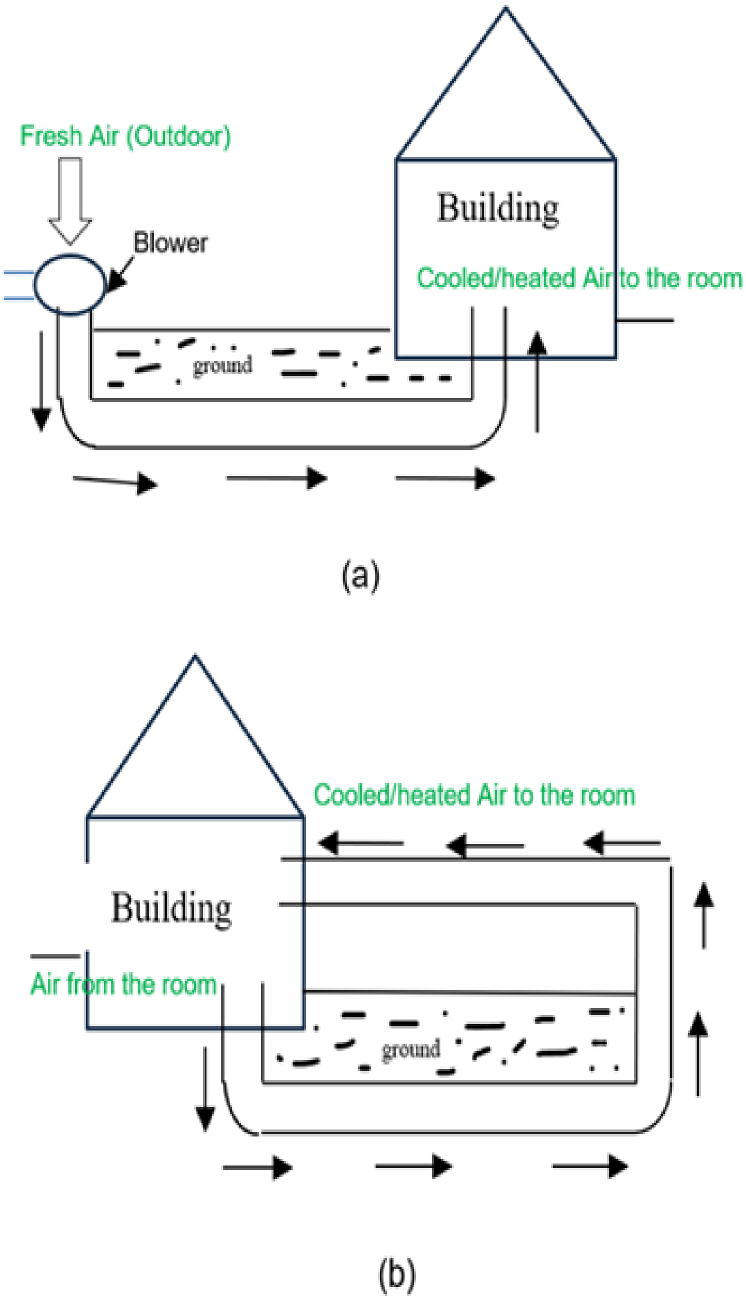


Figure 9. Open loop EAHE (a) and Closed loop EAHE (b)

2.10.4.2. Classification based on layout of the pipe

This category refers to how the pipes are arranged underground.

- **Horizontal EAHE system (HEAHE):** defined by the installation of pipes in parallel to the ground surface (horizontal lines). In both residential and commercial applications, this is the most common approach. It presents specific benefits, among them, its simplicity in the implementation in regions where groundwater levels are shallow and ease of interfacing with building HVAC systems. Although it necessitates a significant amount of space, this system remains easier and more cost-effective to install, specifically, in open areas. However, the thermal efficiency may be influenced by fluctuations in soil temperature and moisture levels, which typically occur more strongly near the surface [104].

- **Vertical EAHE system (VEAHE):** the pipes are positioned in a vertical orientation within boreholes that extend deep into the ground. VEAHE are often preferred in urban or densely populated regions where land is limited, as well as in scenarios that require improved heat transfer rates (access to deep soil and high thermal stability) [105]. This system provides several advantages over horizontal counterparts by utilizing deeper ground temperatures [106]. As the depth increases, the influence of external environmental conditions on ground temperature diminishes. This minimizes the impact of seasonal fluctuations in surface temperature, resulting in more consistent and reliable annual heat transfer. This enhances the overall performance of the system [107], [108]. Nonetheless, it typically requires drilling equipment and higher installation costs.

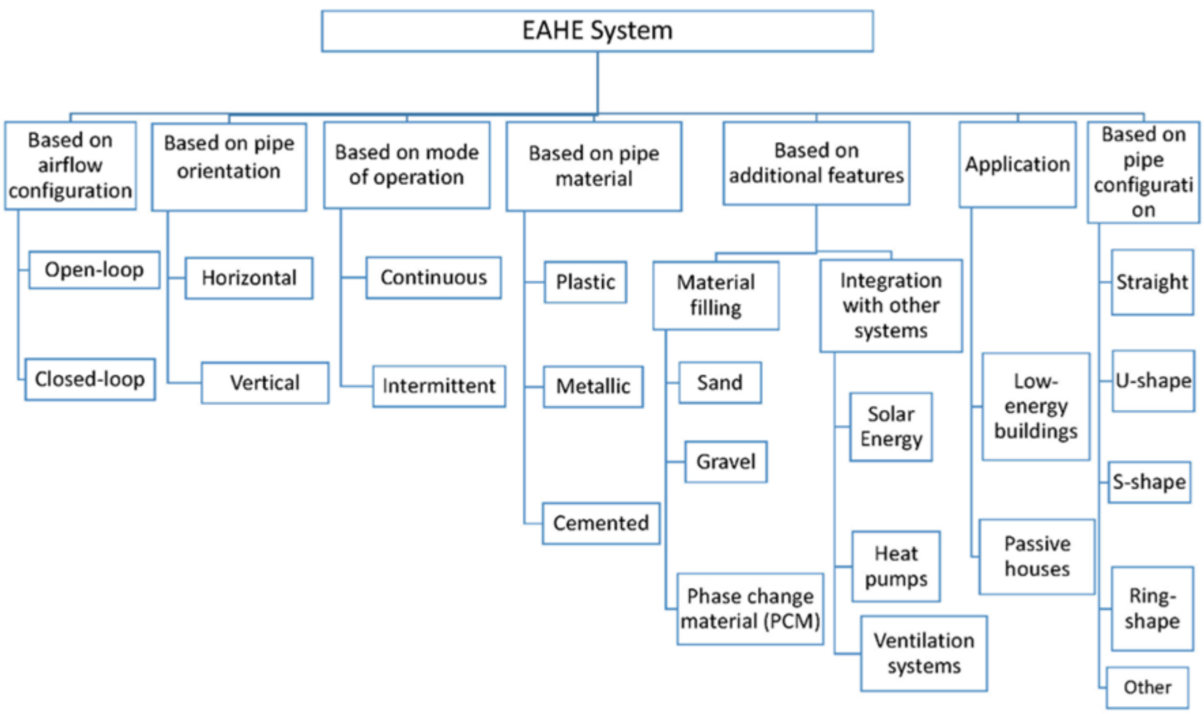


Figure 10. EAHE types based on several categories from literature [109], [110], [111].

2.10.5. Heat transfer mechanisms in EAHE

Heat exchange mechanisms permit the transmission of heat between the ambient air passing in the pipes of the EAHE and the surrounding ground [112]. The fundamental principle of the operation of EAHE is based on two primary heat exchange mechanisms [113]:

A. **Conduction:** This type of heat transfer happens between the wall of the pipe and the air inside it because of the temperature difference of the two. Therefore, when the ventilation air passes through buried tubes, it can lose or gain heat.

B. **Convection:** Convection refers to the mode of heat transfer between the moving air inside the pipe and the inner surface of the duct. It occurs due to the temperature difference between the air and the surrounding ground, which creates a thermal gradient driving heat exchange. In Earth–Air Heat Exchangers (EAHE), convection is primarily forced convection, as the airflow is driven by a mechanical device such as a fan or blower. The rate of convective heat transfer depends on factors such as air velocity, pipe diameter, and the convective heat transfer coefficient. Natural convection may occur only in the absence of forced airflow, but its effect is generally negligible in typical EAHE operation.

2.11. Factors affecting thermal performance of the EAHE

EAHE thermal behaviour is significantly influenced by various parameters which can be categorized into three primary groups: (a) design parameters of the buried pipes system; and (b) environmental parameters that primarily affect the distribution of ground surface temperature. The parameters in the first category comprise: tube diameter, pipe length, air velocity inside the duct, number of pipe and depth of pipe system. The second group include: soil density and specific heat capacity, thermal conductivity of the soil, thermal diffusivity of the soil and soil moisture content. While some researchers show interest in another category, which is rare in the literature in terms of investigations grouping: convective heat flux between the ground surface and the air, latent heat flux resulting from evaporation and condensation process, radiation waves (long or short), various ground covering and vegetation. The majority of researchers have examined the parametric influence in the first category (system design) on the cooling/heating capacity of EAHE systems, while some studies also include elements from the other two categories.

2.11.1. Impact of design parameters

For maximizing the EAHE's thermal capacity in one hand and maintaining cost-effectiveness with high energy efficiency in other hand, an optimized combination of the system design parameters is essential.

2.11.1.1. Effect of buried depth and soil undisturbed temperature

Understanding the distribution of subsurface temperature and its variations with depth is crucial for constructing the EAHE system. The mechanical properties and arrangement layers of the soil, together with the surface cover, influence the distribution of soil temperatures [114]. The consistent temperature of the soil is a vital element in the development of an EAHE system. For homogeneous soil exhibiting constant thermal diffusivity, a prediction of ground temperature at a certain depth x and time t may be done using the following formula [115], [116]:

$$T_{(x,t)} = T_m - A_s \exp\left[-x\left(\frac{\pi}{365\alpha_s}\right)^{\frac{1}{2}}\right] \cos\left\{\frac{2\pi}{365}\left[t - t_0 - \frac{x}{2}\left(\frac{365}{\pi\alpha_s}\right)^{\frac{1}{2}}\right]\right\} \quad (02)$$

where $T_{(x,t)}$ is the temperature of the ground at depth x (m) and time t (s), the average soil surface temperature (°C) is denoted by Tm, As is for amplitude of soil surface fluctuation (°C), and thermal diffusivity of soil is presented by αs (m^2/s; m^2/day), t represents the amount of time (day) that has passed since the start of the calendar year (day) while, t_0 show the soil surface's phase constant (s; days).

Precisely determining the undisturbed temperature of soil is difficult owing to the common absence of information on soil parameters. Moreover, it is designated for typical soil properties. Consequently, the undisturbed soil temperature is a theoretical number that may be considered synonymous with the annual average soil surface temperature of a certain region. Furthermore, the soil surface temperature is often assumed to be equal to the ambient air temperature.

The ground temperature displays a significant degree of depth-dependent fluctuation [117]; consequently, the variation in the ground temperature decreases as depth increases. The ground's constant temperature is typically concluded for a depth of 2.1 to 4.5 meters. Nevertheless, it may exceed this depth in specific locations. In order to optimize system performance and minimize installation expenses, it is crucial to identify the optimal depth for EAHE systems implementation. With regards to this, several theorical and experimental studies are ongoing recently. Mihalakakou et al. [118] examined the impact of pipe depth on at different depths of subterranean piping. The air temperature varied between 7˚C and 32˚C at a depth of 1.6 m, and between 6˚C and 31˚C at a depth of 3.2 m inside the pipe. Popiel, Wojtkowiak, and Biernacka [119] analysed the variance in ground temperature with depth at both bare and grass-covered surfaces. During the summer season, the subsurface temperature at a depth of 1 m was measured to be 4°C higher on the bare surface than in the grass-covered surface. Depth variations are influenced by factors such as local ground temperature profiles, soil properties, and climate conditions. Babar et al. proposed 3.96 m as appropriate for Sahiwal, Pakistan and Khan et al. [120] recommended 4.5 m for Lahore, Pakistan while Sanusi et al. [121] established that 1 m is the optimal depth in Malaysia. The cooling and heating potential of the EAHE system typically increases with installation depth; however, beyond a certain depth, no significant performance improvement is observed in the EAHE system. The cost associated with excavating the trench rises as the depth of the pipe increases. Badescu [122] noted that the performance of the EAHE system is not influenced by burial depths greater than 4 m from the earth's surface. Nonetheless, the pipe located at a depth of 2 m from the ground surface presents an effective balance between excavation expenses and heating/cooling capabilities. The literature indicates that the ideal depth for EAHE pipe is influenced by various geographic and climatic conditions. Consequently, it is essential to optimize the pipe depth for the installation of the EAHE system at the specific and particular site to ensure maximum efficiency.

2.11.1.2. Effect of material and thermal conductivity of the pipe

As previously stated, one of the factors influencing the EAHE system performance is the pipe material. Materials with higher thermal conductivity provide a superior heat transfer rate, hence facilitating a more effective reduction of the buried tube outlet temperature. Recent studies have insufficiently clarified the primary motivation for the selection of pipe materials in their separate analyses. However, it may be stated that the choices were determined by the cost and availability of materials.

Researchers globally assessed the influence of various pipe materials (including polyethylene aluminium, cast iron, aluminium, plastic and concrete) on the thermal performance of the EAHE system and found no substantial effect of pipe material on its thermal performance. Rosa et al. [123] examined the influence of many design attributes, including the pipe material. They noted that the pipe had no meaningful impact after the transition from PVC to steel. Hatraf et al. [124] conducted a parametric analysis to assess the air temperature profile inside tubes under Algerian settings. They verified that the pipe material does not influence the thermal performance of the heat exchanger. Bansal et al. [125] evaluated the performance of the EAHE system by CFD modelling in summer under analogous settings, demonstrating a cooling range of 8.1 - 12.8 °C relative to the ambient temperature. Further, in another study by them, Bansal et al. [126] examined in Western India, Ajmeer the system behaviour in winter season. The pipes were dug up at 2.7 m on arid (dry) soil of flat land. They conducted experiments on steel and PVC pipe materials with air velocities of 2 to 5 m/s, length of 24 m and diameter of 0.15 m. the outcomes indicated that the system provides warmth within the range of about 4 to 5 °C. Thus, the conclusion was that since the material has no effect on the EAHE system's performance, the less expensive material should be utilized to the pipe construction. Menhoudj et al. [127] conducted a comparison of the performance of the EAHE system using two distinct pipe materials, PVC and Zinc. The findings revealed a minimal air temperature drop of 6°C for the PVC pipe and 6.5°C for the Zinc pipe. According to the literature, a little (negligible) effect of pipe material on EAHE thermal performance is conducted by the aforementioned study results. Because of its inexpensive cost, good corrosion resistance, flexibility, and ease of installation, PVC pipe is preferred for the EAHE system. To further improve pipe hygiene, an antimicrobial coating may be placed into the inside of the pipe.

2.11.1.3. Effect of pipe diameter

Rosa et al. [128] investigated the impacts of pipe distance, pipe diameter, and air flow rate. The primary factors affecting EAHE effectiveness are the pipe diameter and air velocity. Moreover, the separation between the two pipes may be reduced to 0.5. In Egypt, Serageldin et al. [129] assessed the thermal performance of an EAHE system that was designed and placed to provide building air conditioning. The investigation focused on the impact of different operational parameters and designs, including airflow velocity, spacing between pipes, pipe length, duct material, and pipe diameter, on the system's performance. The results demonstrate that various characteristics have a noticeable impact on air temperature. As the diameter of a pipe increases, the temperature of the air decreases. when the pipe diameter increases from 0.5m to 0.76m, the air temperature output decreases from 20 °C to 18.6 °C. Furthermore, an increase in pipe length results in a corresponding rise in the temperature of the air at the end of the pipe. In an EAHE system, extending the length of the pipe enhances the variation in air temperature between the inlet and outlet, while an increase in pipe diameter leads to a reduction in this temperature difference [130], [131]. In an investigation of system behaviour, Agrawal et al. [132] used 0.05m, 0.075 m, and 0.1m pipes. After 6 hours of continuous operation, they found that for dry soil, EAHE reduced air temperature by 13.5 °C, 11.4 °C, and 8.6 °C; for wet soil, EAHE reduced air temperature by 13.2 °C, 12.2 °C, and 11 °C (with a moisture content (MC) of 5%). The findings indicate that a larger pipe diameter leads to a lesser reduction in air temperature. This can be explained by the observation that enlarging the pipe's diameter extends the distance from the pipe's centre to soil layer. The study of Zhang et al. [133] examined the impact of pipe diameter. The range is from 100 mm to 200 mm, which influences the airflow rate within the buried pipe. They conducted that enlarging the pipe diameter leads to a slight impact on the outlet air temperature, causing a modest increase in summer and a reduction in winter. The precooling performance and daily cooling capacity vary between 9.5 °C and 9 °C, as well as from 20 kWh to 19.6 kWh, respectively. Further, the influence of the underground pipe diameter of the EAHE indicates that a larger diameter results in lower outlet air temperatures for a thermal power plant during winter and elevated temperatures in summer [134].

2.11.1.4. Effect of pipe length

An extended pipe length improves cooling efficiency by prolonging the air's contact time with the pipe surface, facilitating enhanced heat exchange, as noted in EAHE systems built in Spain [134]. Additionally, it was confirmed that air passing duration in the EAHE increases with increasing the pipe length resulting in improving thermal efficiency of the system based on the investigation of Derbel and Kanoun [135]. The analyses of Serageldin et al. [129] in the Egyptian climate demonstrate that an increase in pipe length results in a corresponding rise in the outlet air temperature. Pipe length increment of about 2m (4.9 m to 7m) results in a temperature elevation from 19.5 °C to approximately 20.2 °C. Moreover, increasing the pipe spacing from 20 to 50 cm results in minimal variation in the exit air temperature, shifting only from 19.6 °C to 19.7 °C. The air temperature of the EAHE system decreases in the summer and rises in the winter as the pipeline length grows, as noted by Lee KH et al. [136]. However, no substantial benefits of using EAHE pipe above 70 m in length. The impact of soil types, air temperature within a greenhouse, and the length and diameter of subterranean pipes, as well as their depth and mass flow rate, were investigated by Ghosal and Tiwari [137]. According to the findings, the EAHE performance was directly impacted by a 30-to-50-meter increase in pipe length. Hence, an increase in air temperature dropped in the summer and rose throughout the winter. The results of a study conducted by Zhang et al. [133] suggest that a pipe length of 80 m is optimal for achieving effective pre-heating and pre-cooling performance in the EAHE-assisted building air conditioning system throughout the year. Considering the equilibrium between thermal efficiency and construction costs of the EAHE system, further extending the pipe length may not yield advantageous outcomes.

2.11.1.5. Effect of air velocity in the buried pipe

Cooling and heating capabilities of the EAHE are highly dictated by air flow [138]. The impact of air velocity on the EAHE system's capacity to sustain thermal comfort was examined in research conducted by Mihalakakou et al. [139], [140], [141]. These scientists measured the effect of a small change in air velocity on the output temperature of the EAHE system. The outcome has been shown that the heating capacity of the system diminishes with increasing velocity of the air. Rosa et al. [128] noted that air velocity significantly influences the thermal performance of the earth–air heat exchanger system. Further, Zhao et al. [142] observed that when air velocity rises, the efficiency of temperature extraction diminishes. For space cooling, Ahmed et al. [131] conducted a comprehensive sensitivity study about the thermal efficacy of a horizontal EAHE system. Most of the design characteristics system were examined.

Concerning air velocity, four measurements were evaluated: 2 ,1.5, 1 and 0.41 m/s; it was determined that 1.5 m/s provided the optimal cooling capability. The influence of diverse airflow velocities was examined at four distinct levels: 2, 5, 8, and 10 m/s [132]. This research determined that increased airflow velocity results in thermal losses from the pipes to the adjacent soil, significantly affecting the air temperature negatively.

2.11.2. Impact of environmental parameters

As is mentioned above, the environmental parameters attached to this work include soil proprieties (thermal conductivity, specific heat capacity, thermal diffusivity, moisture content and density) in addition to soil coverage predominantly affecting the distribution of ground surface temperature. Soil characteristics substantially affect thermal conduction in the subsurface. Sand, clay or loam as soil type play a huge role in finding out its thermal properties. Typically, in comparison to sandy soil, good content of clay within clay soils offers higher thermal conductivity [109], [143]. In this regard, Agrawal et al. [144] conclude soils having elevated thermal conductivity, such as clay-rich soils, often demonstrate superior heat transmission compared to sandy soils. Deglin et al. [145] conducted a comprehensive examination of the impact of several parameters from the first category (design parameters) including length of the EAHE tube, its diameter, its material, the speed of the air inside the tube and the soil type from the second category. Two independent soil types were chosen: saturated slit and dry sand. The outcomes show that the soil with higher saturation was the most effective one, thus higher thermal conductivity. However, the specific features of each soil type can differ considerably based on elements like porosity, distribution of particle size and mineral composition. Further, the efficacy of the EAHE system is significantly influenced by ground surface conditions due to their impact on soil thermal conductivity; in this context, the primary parameters investigated include different ground coverings, namely (a) bare soil and (b) short-grass soil, as examined by Mihalakakou et al. [118] for space cooling and by Mihalakakou et al. [141] for space heating. The system's potential was examined and evaluated in both cooling and heating operational modes. Research indicated that short grass soil, as a ground surface cover, significantly enhanced the system's cooling capacity, while bare soil was shown to augment the system's heating capacity.

The thermal conductivity is greatly affected by moisture content. The existence of water within the soil matrices typically improves heat transfer because of high thermal conductivity of water [146], [147]. However, an overabundance of moisture may lead to adverse consequences. An elevated moisture level may result in greater soil density, potentially obstructing heat transfer. Furthermore, it may lead to the deterioration of underground pipes, affecting their durability and performance [148].

Table 4. Summary of parameters influencing thermal behaviour of EAHE

Type of design parameters	Impact on system	References
Depth of installation	Deeper layers provide more consistent soil temperatures, thereby improving system efficiency, particularly in areas experiencing significant variations in surface temperatures. The thermal performance of the EAHE system enhances with increased depth, as the time lag between underground and ambient temperatures grows with the depth at which the pipes are buried. It was noted that the enhancement in performance was minimal beyond 4 m of depth.	[117], [118] [119] [120] [121] [122]
Material of EAHE pipe	The pipe material has a minimal almost negligible effect on the thermal performance of the EAHE system. Therefore, the cost of the pipe, its durability, and its resistance to corrosion are crucial factors in selecting the appropriate pipe material. PVC pipes are preferable because of its affordability, flexibility, excellent corrosion resistance, and simplicity of installation.	[123] [124] [125] [126] [127]
Diameter of EAHE pipe	Large diameter allows higher air flow, resulting in lowering heat transfer efficiency due to less contact of air with the pipe wall. Therefore, effective cooling/heating performance can be achieved through a smaller diameter.	[128] [129] [130], [131] [132] [133] [134]
Length of the pipe	Generally, with a constant diameter longer tubes led to improved performance because of higher heat transfer with the soil. However, it increases pressure drop, resulting in increment of energy used by the blower. The rate of heat transfer diminishes significantly when the temperature of the fluid (air) within the pipe approaches that of the surrounding underground soil. At this stage, any additional length does not affect	[128] [129] [130], [131] [132] [133] [134]

	the temperature of air. From the outcomes 80-120m is the recommended pipe length.	
Fluid velocity	The volume of the air treated inside the pipe increases by increasing the speed of the airflow. That plays on shorting the time the air spends in contact with the pipe wall, which might lower the efficiency of the heat exchange. Most luckily better thermal performance is achieved at lower air velocities compared to higher flow rates. Thus, optimization of flow rate is required depending on the application.	[138] [139], [140], [141] [128] [142] [131] [132]
Soil type	Soil with higher thermal conductivity enhance the EAHE thermal performance due to the faster heat transfer between the soil and pipe wall. Soil that has high volumetric heat capacity (either moist or dense soils) can store more energy, allowing a sustain exchange of temperature for longer periods without rapid exhaustion.	[109], [143] [144] [145] [118] [141] [146], [147] [148]

2.12. Influence of pressure drop on the EAHE performance

Based on several studies in the scientific literature, pressure drop (equivalently, airflow velocity) is a key aspect that affect the EAHE thermal performance, mainly through its influence on energy consumption of the fan and system thermal efficiency. Pressure drop directly influences the air flow rate through the buried pipes, which in turn affects the thermal effectiveness of the heat exchanger. Computational and experimental studies have proved that achieving the target of balancing thermal performance with the energy cost of air movement comes from a good optimization of the pressure drop inside the pipes. Various authors demonstrate in their research that the pressure drop depends on velocity of the air passing in the tube thus, on pipe diameter too. Larger diameters result in lower air velocity; therefore, lower pressure drops. In the same way, smaller diameters consequence in higher air velocity; hence, higher pressure drops. Higher pressure drops lead to increased fan power consumption, thus reducing overall system efficiency. In arid climates, a study of an EAHE by Abdessamia [149], concluded that the temperature drops of air increases with decrease in air velocity. When the EAHE system operate at air velocity of 10m/s the temperature drop is 7.9 °C whereas when it functions at 20 m/s air velocity, it only managed 4.9 °C. This research illustrates a clear trade-off between pressure drop and thermal return. Bisoniya et al. [150] conducted that better heat transfer gain with higher pressure losses and both the pressure drop and NTU (Number of Transfer Units) increase with increasing EAHE pipes. Additionally, they suggested J-Factor (pressure drop/NTU) can be applied for great evaluation of thermo-hydraulic performance. In another study by the performance of an EAHE was analysed using three diameters 0.0485, 0.038 and 0.0285 m and various air speed (6.5, 5, 3.5 and 2 m/s).

2.13. Experimental validation and modelling approaches of the EAHE

EAHE models' validation with experimental setup is crucial to guarantee the system reliability and accuracy in predicting their performance. That get into comparing model outcomes and results with the real-world dataset and measurements from EAHE system. This assesses the model ability to capture comprehensive interacting with the surrounding soil and the system thermal behaviour. Based on literature several researchers have validated their numerical and analytical EAHE models with experimental measurements and confirmed the feasibility and the reliability of their developed simulations.

An analytical three-dimensional transient model for forecasting the thermal performance of a subsurface EAHE system for air-conditioning of a livestock house was developed by Deglin et al. [145]. Convectional heat transfer mechanisms between the soil and the air inside the pipes were the primary basis of the model. Experimental data was used to effectively verify the theoretical conclusions. Hasan et al. [151] conduct a parametric study of the earth–air heat exchanger for applications in both heating and cooling operation modes in Nasiriyah city, southern Iraq. Their numerical studies demonstrate the impact of different designed parameters on overall system performance. Where the numerical model was validated against the experimental model, revealing a strong correlation between the two. Qin et al. [152] conducted an enthalpy-based numerical model using control volume method for prediction of energy and thermal performance of a combined system of geothermal and solar energies. The prediction outcomes of the model were successfully validated using on-site experimental test rig of phase change material-based solar air heater coupled with EAHE in Changsha, China. The results show that the output temperature may stay between 33 and 35.9 °C for more than 4 hours when PCM is used, and the heating capacity fluctuation is reduced by 38%. Diedrich et al. [153] focused on developing a computational model and subsequently subjected it to physical validation to assess the thermal performance of an EAHE system. The comparison between the computational and experimental results pointed a strong similarity, with a maximum difference of 3 % observed under the analysed conditions. The simplified model applied to the soil domain demonstrated its effectiveness for the EAHE simulations, successfully reducing computational time while eliminating the need for local climatic conditions as a boundary condition. Consequently, average soil temperatures that are estimated or derived through experimentation may be utilized. In another study, Liu et al. [107] offered an alternative to the standard HVAC system which is the VEAHE. An experimental setup was put up to study the fluctuation of its air temperature along the pipe, outlet air temperature, and soil temperature after they confirmed its thermal and economic viability. In order to evaluate the suggested system economically, they also computed its energy metrics. Because there was a high degree of agreement between the model's simulations and the actual experiments, the results proved that the model is feasible. Merdassi and Aouissi [154] compared the performance of two different EAHE design (spiral and serpentine) using ANSYS Fluent software for numerical simulations. The model was based on varying three various parameters, air flow rate, length pipe and inlet temperatures. The focus of the simulations was on the pressure losses and the outlet temperatures at 2 and 3m depths.

The models' accuracy was confirmed by comparing them to experimental data for numerical findings for spiral and serpentine designs.

2.14. State of the art of Earth - Air Heat Exchanger and research scope

The use of EAHE, which may offer natural ventilation and use the consistent ground temperature to provide cooling and heating, is one substitute for traditional heating and cooling systems. An examination of the various methodologies found in the literature allows for the identification of the different hypotheses and simplifications related to the use of Earth air heat exchangers, together with the mathematical representation tools used, which are reliant upon the model's aims. Multiple studies have been done on the integration of EAHE system in civil building and greenhouses. Research has anchored on enhancing several features of EAHE systems, including design, operation, and performance evaluation. In 2002, Kabashnikov et al. [155] presented one of the initial one-dimensional models of an earth-to-air heat exchanger. The mathematical model was straightforward, and the results gathered were limited. A mathematical analysis was conducted using Fourier integral to assess the temperature within the system, while varying the length, diameter, and depth of the ducts. The primary outcome of the model is an analytical expression that yields the mathematical values for the length and diameter that optimize heat exchange between the ground and the air. In the followed year, De Paepe and Janssens [156] presented to the scientific community their one-dimensional analytical model, which incorporates convective heat exchange by calculating the convective coefficients using a dimensionless numbers approach. They evaluated the influence of pressure drop as function of volumetric flow rate, of diameter and length of the duct. They noticed that smaller diameters provide higher thermal performance, but greater pressure drops. The proposed solutions involve projecting EAHE with additional pipes arranged in parallel to address these opposing trends. An EAHE system was installed inside an earthen house by Chel and Tiwari [157]. Indoor air temperatures were 5–15 °C higher than outside air temperatures throughout the winter, according to the author's research. A projected annual energy savings of 5375 kWh was also a consequence of integrating the EAHE system. In France, researchers tested an EAHE to see how well it could heat and cool a 380 m^2 dining room. Eleven pipes were interconnected with this system and laid underground. The pipes had a depth of 2 m and a diameter of 0.2 m. Over the course of July and August, the outcome was a cooling power output of 14 kW, with a flow rate of 7200 m^3/hour [158]. Belloufi et al. [159] studied the cooling mode behaviour of the EAHE under transient conditions for the semi-arid climate of Algeria. The system had a single horizontal coil that was 53 m long and 85 m^2 surface area. According to their results, the EAHE successfully reduced the air temperature to 30 °C by creating a temperature differential of about 10 °C. Li et al. [160], [161], [162] performed a series of experimental and computational investigations on the thermal efficacy of the EAHE system in a severe cold environment. The findings indicate that the EAHE system can provide an average preheating capacity of 14 °C under heating conditions. Siepsiak [163] assessed an EAHE approach in Poland for a period of about three years, using energy efficiency as an indicator across several refreshing settings. The system delivered roughly 124 W of cooling per hour and 257 W of heating. This underscored the system's capacity to enhance interior thermal comfort. The results were useful in determining the optimal HVAC system configurations for engineering projects. Bordoloi et al. [164] in their review study categorized and evaluated the energy performances of EAHE systems, detailing the most significant analytical and experimental investigations on various EAHE combinations up to the year 2018. Their review emphasised that system performance is highly sensitive to site-specific factors, including soil thermal properties, pipe geometry and climatic conditions, and that hybrid configurations like combining EAHE with heat pumps or Air Handling Unit consistently outperform standalone systems in terms of overall energy efficiency and thermal comfort enhancement. Kaushal [165] carried out an experiment in the Lower Himalayan region, where an EAHE system with an airflow rate of 0.5 m/s and a pipe length of 60 m exhibited a peak heating potential of approximately 28 kWh and a cooling potential nearing 15 kWh. The EAHE system has played a significant role in decreasing energy consumption for heating by around 25–30% [166]. Goyal et al. [167] developed and tested an innovative bank-type EAHE in a controlled experimental setup. The study focused on evaluating its performance under the hot, dry, and humid climate conditions of Ferozepur, India. The system successfully reduced the ambient temperature to 29 °C, and the results showed greater accuracy compared to their earlier studies. Furthermore, Xiao et al. [168] investigated the thermal behaviour of an EAHE system integrated into a greenhouse in Northern China. The research merged CFD simulations with experiments to assess the system's effectiveness across different seasons. The outcomes of the investigation indicate that the EAHE system raised the greenhouse's night-time air temperature by 1.4 °C in winter, while in summer it decreased the daytime air temperature by 2 °C. Moreover, the variations between the EAHE’s inlet and exit air temperatures were 10.6 °C in summer and 9.3 °C in winter with an efficiency of 24% and 22.5%, respectively. Researchers from France [169], Italy [170] ,Brazil [153], Bangladesh [171], China [172] and the United States [173] also conducted analogous tests under local climate conditions. Additionally, in order to compare traditional and heat exchanger-ventilated systems, Ahmed et al. [174] buried 20 horizontal pipes over an area of 16 m^2, each measuring 7.5 m in length and 0.7 m in depth. When the outside temperature was more than 34 °C, the temperature differential could not be more than 2 °C. Using a complete factorial study, Khorchef et al. [175] determined the best winter and summer EAHE setups. The airflow, the length of the pipe, and thermal conductivity were the three main factors for their model. The study shows that air velocity is a major factor, thermal conductivity is a minor but significant one, and pipe length is the most important factor when it comes to controlling the temperature. In the winter, the pipe length accounted about 59% of the variation, whereas in the summer, it was over 49%. Another investigation [176] examined the efficiency of an EAHE system in Bechar, Algeria. The setup had a PVC pipe with a diameter of 11 cm and a length of 66 m, buried at 1.5 m under the ground. During the humidification, this system achieved an increment of 19% in relative humidity and a drop of 27% during dehumidification. These findings highlight the EAHE's capability to improve hygrometry of buildings in arid regions. D'Agostino et al. [177], [178] evaluated the thermal performances of EAHE compared to air-to-air heat exchangers providing promising energy savings also for this configuration but with higher economic costs. In Lanzhou, China, Zhang et al. [179] studied EAHE operation and energy efficiency. The study determined that the ideal system parameters for such site, as determined by orthogonal simulation, are an airflow velocity of 7 m/s, a pipe length of 20 m, a burial depth of 4 m, and a diameter of 0.1 m. These selections enhanced heat transfer efficiency by 38% and reduce unit heat transfer cost by 8,000 CNY/kW compared to the original design. Brata et al.

[180] evaluated the performance of a EAHE in Timisoara, Romania. The system featured a 35 m long exchanger pipe with a 0.2 m diameter, buried at a depth of approximately 2 m. During winter, it supplied around 31% of the energy required by the ventilation system. A study of EAHE systems with pipe lengths between 67 and 107 m, buried at approximately 2 m, and functioning under different air velocities (500 m³/h, 2500 m³/h and 3000 m³/h) was conducted in Germany. A variation of 16 to 51 kWh/m² was realized for the yearly heating energy outcome of the system, while between 12 and 23.8 kWh/m² was reported for the annual cooling energy gain [93].

Table 5. Summary of novel case studies of the EAHE thermal behaviour in different sites

Authors	**Installed location**	**Performance achieved/design parameters**	**Year of research**	**Reference**
Siepsiak	Poland	The system featured a length of 41m, diameter of 0.2m and the pipes was buried at depth of around 2m. The research conducted in sandy soil and the system supplied approximately 257 W of heating and 124 W of cooling per hour.	2022	[163]
Kaushal	The Lower Himalayan Region	The configuration features a pipe length of 60m and an airflow rate of 0.5m/s. With a maximum heating capacity of 28 kWh and a cooling capacity of about 15 kWh. The system contributed to reducing energy consumption for heating by almost 25–30%.	2021, 2017	[165]
Goyal et al.	Ferozepur, India	Try out EAHE in this hot, dry, and humid environment to see how it works. The results reveal that the outside temperature has dropped to 29 °C.	2023	[167]
Xiao et al.	Northern China	The differential between the input and outlet air temperatures of the EAHE was 9.3 °C in winter and 10.6 °C in summer, with an efficiency of 22.5% and 24%, respectively.	2023	[168]
Zeitoun et al.	Northeast of France	The setup built at ICUBE at the University of Strasbourg for heating period between 25 February and 3 March. The findings indicated that the system gained approximately 63 kWh of heat energy, with an average exergetic efficiency of around 57%.	2023	[169]

Cirillo et al.	Italy	The study used a two-dimensional numerical model which include the surface, soil and the buried pipes. The use of the EAHE in HVAC systems diminishes energy consumption throughout diverse Italian climatic zones by: 23% to 43% in cooling mode and 30% to 45% in heating mode. Additionally, the investment at the conclusion of its lifespan (25 years) is consistently positive.	2024	[170]
Diedrich et al.	Brazil	The EAHE was installed at the Federal University of Technology—Parana, Ponta Grossa/Brazil. Authors fixed tube surface temperature at 23.7 °C, reflecting average soil conditions at 1.5 m depth. The simplified CFD models exhibited a deviation of no more than ~3.1% from real data, signifying high accuracy.	2023	[153]
Hassan et al.	Bangladesh	Based on the observed effects of relevant parameters on the outlet Temperature, two geometric configurations were designed and analysed. The EAHE effectively cooled the simulated room to about 28ºC, compared to the ambient temperature of 35 ºC.	2024	[171]
Li et al.	China	Application of EAHE model in Passivhaus (passive house) standard building for various climate conditions. The outcomes indicated that the system achieved an annual building energy load saving of up to 12.8 kWh/m^2 in regions with hot and humid summers and cold winters (Beijing and Shanghai).	2023	[172]
Zajch et al.	United state	Geo-climatic suitability of EAHE across 273 sites in the Americas, both under historical climates and future climate-change scenarios. The finding based on the future projections showed that warmer zones will experience increment in cooling demand while the coolest climates will have reduced heating	2020	[173]

		potential. Additionally, Areas that have traditionally maintained a balance between heating and cooling requirements were recognized as possessing the greatest potential for future EAHE applicability.		
Ahmed et al.	Rockhampton, Australia	The investigation conducted a horizontal EAHE system and the impact of the soil temperature, air velocity and the soil temperature on the EAHE performance. As results 2.3ºC was a reduction of air temperature with an amount energy saving equal to 416 kWh for summer. This leads to in a total energy cost savings of AU$190.	2022	[174]
Sakhri et al.	Bechar, Algeria	The system consisted of a 66 m long PVC pipe with a diameter of 0.11 m, buried at a depth of 1.5 m below the surface. During dehumidification, the system resulted in a 27% reduction in relative humidity, while during humidification, it achieved a 19% increase in relative humidity.	2020	[176]
Zhang et al.	Lanzhou, China	The best system settings are 7m/s airflow velocity, 20m pipe length, diameter of 0.1m, and burial depth of 4m. This design unit heat transmission costs by 8,000 CNY/kW and increases efficiency by 38%.	2024	[179]

To the best of the researcher knowledge, the current state of research has a limited evaluation of an EAHE implemented upstream an AHU specifically for Central European climates including Budapest [181], [182], [183] design day coil load reduction as it is reflected in the figures 11 and 12.

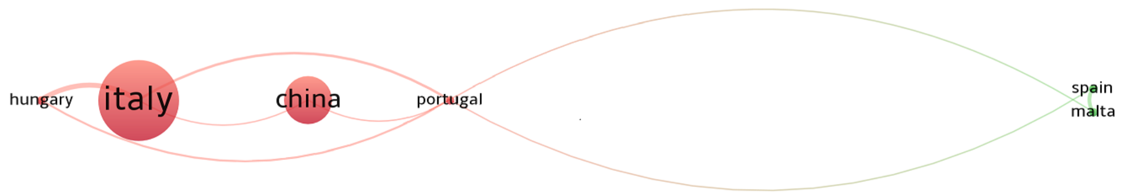


Figure 11. network of bibliographic coupling among nations engaged in the study of EAHE combined with AHU.

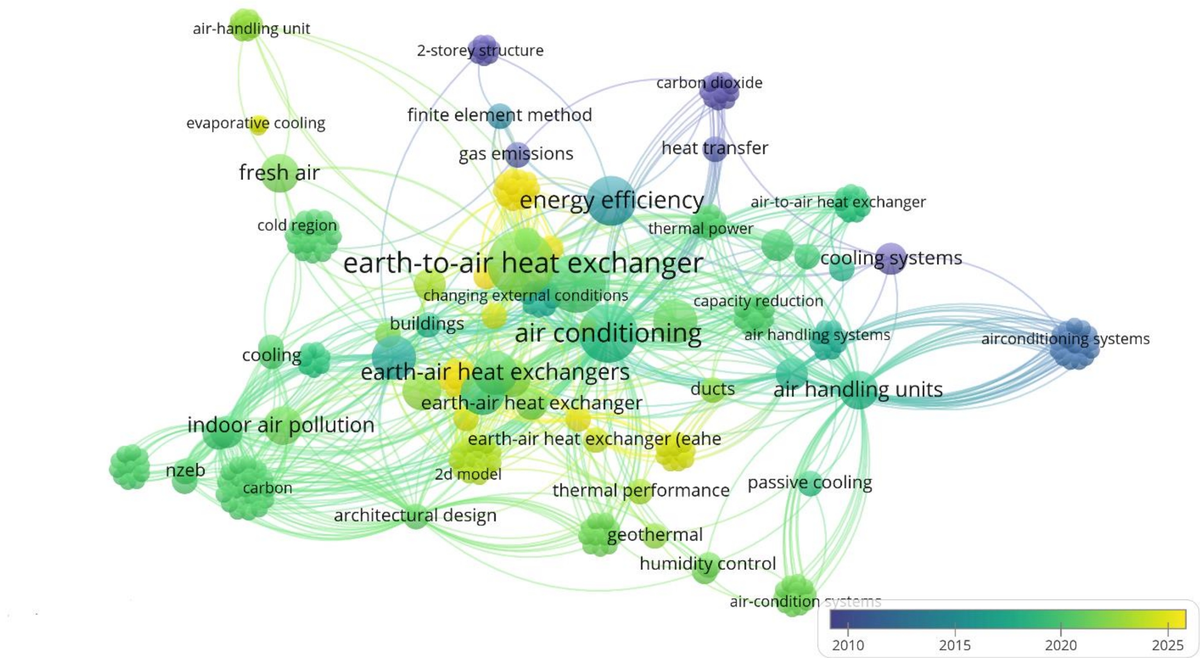


Figure 12. Visualization of keyword co-occurrence in EAHE–AHU research (data retrieved from Scopus database on 27 January 2025)

By using VOSviwer software, a bibliographic coupling network of countries active in research on Earth–Air Heat Exchangers integrated with Air Handling Units is done and the results are presented in Figure 11. Where the dominant contributor and central intellectual hub according to the analysis is Italy, showing a high bibliographic connection to China, Portugal, and Hungary and meaning that these countries shared theoretical and methodological foundation. Italy and China are currently the primary countries conducting such research, yet Hungary's involvement in this central cluster is especially significant, as it indicates emerging but still limited research activity within the climate and geographical context of the broader EAHE–AHU literature. A secondary cluster that includes Spain and Malta indicates a research focus that is more sensitive to regional contexts, likely shaped by Mediterranean climatic conditions. Meanwhile, Portugal serves as a transitional unit connecting the central and remote clusters. Overall, the limited number of participating countries and the disjointed nature of the network suggest that EAHE–AHU research has not achieved global integration, with collaboration and shared knowledge primarily concentrated within a small group of regions. This irregular geographical distribution highlights a clear research gap, particularly regarding the application and evaluation of EAHE–AHU systems in Central and Eastern European areas. In this context, the current investigation is driven by the necessity to enhance the evidence foundation for EAHE–AHU performance beyond existing research and wider international integration of this developing subject as the Fig.12, illustrated the temporal evolution of the field based on average publication year.

At this aim, a case study of school building is analysed and virtually collocated in diverse climatic zones in Europe. The HVAC system is based on fan-coil units, and the EAHE is installed upstream the AHU for primary air. In light of the aforementioned considerations regarding model dimensions, a two-dimensional mathematical model of the EAHE was adopted from literature to investigates the impact of integrating an Earth–Air Heat Exchanger upstream of an Air Handling Unit in a school building, with the aim of quantifying reductions in peak heating and cooling coil loads through a psychrometric-based evaluation of air pre-conditioning under design-day conditions. The approved EAHE features 40 horizontal circular ducts arranged in parallel at a depth of 2.5 m. The EAHE is regarded as a device that pre- heat or pre-cool the open-loop airflow (primary air) of the AHU. The school building is essentially situated in two European countries (Hungary and Italy) for comparison purposes. These countries belong to different climatic zones according to Köppen climate classification. The EAHE simulated and optimized as a function of air pipe diameter and length. The following parameters are examined: thermal efficiency of the EAHE; the coils power needed by the AHU with and without EAHE and the reduction of design heating and cooling capacity of the AHU coils when coupling it with EAHE. The analysis on the coils of the AHU is performed for both season winter and summer.

After a comprehensive analysis of the state of art, it is clear that the thermal behaviour of the EAHE cannot just be affected by the soil type but mainly with the local climatic boundary conditions where the system is installed. For these reasons, the primary novel contributions of this study are as follows:

- The suggested comparisons using various categories of climatic conditions in Europe, Mediterranean and continental climates.
- The EAHE has typically been researched as an independent unit, but this work analyses a hybrid air conditioning system in which the EAHE serves as pretreatment unit. It is placed upstream the air handling unit to decrease the energy needs.
- For different European climatic zones, the thermal efficiency of the EAHE is evaluated, additionally to the drop off cooling and heating capacity of the coils into the AHU.

2.15. Integration of EAHE with HVAC system and Air Handling Unit

2.15.1. Nutshell of Air Handling Unit

A central component of mechanical ventilation and HVAC system with the role of maintaining thermal comfort and ensuring indoor air quality in building is named as AHU. Buildings such as schools, hospitals, industrial facilities and large-scale offices, required a controlled indoor environment thus, are typically supplied with such mechanical ventilation system. The main role of the AHU is to provide sufficient ventilation, guarantee the purity of indoor air, and distribute air at the necessary humidity and thermal levels. To condition the air a base AHU uses several components that process together to achieve the desired indoor conditions. These include filter to eliminate particulate contaminants, cooling and heating coils (either refrigerant-based or water-based) where the sensible and latent loads are addressed by exchanging heat with hot or chilled water generated by an external source such as boiler, chiller or heat pump. These coils play the key role in regulating the supply room air temperature. Their performance strongly depends on the humidity and temperature of the fresh/incoming air (outdoor air conditions).

Regrading conventional HVAC system, especially during peak winter and summer seasons, the AHU is functioning to handle the entire thermal load associated with the outdoor air conditions. However, AHU receive pre-conditioned air, warmer in winter and cooler in summer after incorporated it with EAHE. This combination leads to reduce coil load and therefore lowing the energy demand, all in the aim of improving the overall system efficiency.

2.15.2. Hybrid-EAHE system

Multiple research papers support the notion that both the efficacy and practicality of the EAHE system can be enhanced by integrating it with other either active or passive systems. The passive setup utilizes just a small quantity of electrical energy, while the active system requires a substantial amount of electrical power. Consequently, to minimize the thermal load and overall power consumption of active systems (like air conditioning systems), EAHE system can be combined with various active systems [91], [184]. Baglivo et al. [185] introduced a setup specifically designed for Mediterranean climate that integrate a horizontal air-ground heat exchanger (HAGHE) also, referred to as EAHE with the air-cooled heat pump (ACHP). During the summer, the heat pump condenser received pre-cooled air from the EAHE system, while in winter, pre-heated air from the EAHE was directed to the evaporator. The analysis revealed that approximately 1114 kW h of energy can be conserved each year by implementing the EAHE system in conjunction with the ACHP, in contrast to the standalone ACHP system. Recent studies have shown the potential of integrating EAHEs with air source heat pump (ASHP) to enhance the effectiveness of building cooling and heating equipment. Investigations carried out by Congedo et al. [186], Mahmoud et al. [187], Guo et al. [188] and others have demonstrated encouraging outcomes across diverse climatic scenarios. In northern Italy, for a single-family home Cavazzini et al. [70] carried out an in-depth investigation to assess the efficiency of an air-source heat pump combined with an EAHE. This investigation sought to evaluate the system's performance in practical operating scenarios and measure the advantages of integrating an EAHE with an ASHP. While ASHP have typically been used to transfer heat between air and water for the purposes of space heating and cooling, this innovative method introduces a new step where the air is preconditioned by flowing it through an EAHE prior to its entry into the ASHP. Furthermore, the combination of EAHE and PV systems presents a compelling approach to enhance energy efficiency in buildings significantly. These hybrid systems possess numerous potential purposes, such as the pre-cooling and pre-heating of supply air, temperature regulation for photovoltaic panels, and the advancement of Combined Cooling, Heating, and Power (CCHP) systems [72], [189]. Other researchers [190], [191] investigated a hybrid system that combines an EAHE with phase change material (PCM) ceiling boards to facilitate passive cooling. This system proficiently manages indoor temperature, optimizes energy efficiency, and elevates occupant comfort. This system is designed for areas where natural ventilation fails to provide adequate comfort due to elevated outdoor temperatures, making it ideal for hot and humid climates. Li et al. [160] examined the practicality of using an EAHE in together with an AHU for the preheating of fresh air. Their findings indicated that in extremely cold regions, this combined system raised the air temperature by 26 °C, with 14 °C attributed to the EAHE system and the remaining 12 °C from the AHU. Consequently, this hybrid system delivered adequate heating to the air independently of any supplementary heating system. To enhance the first law thermodynamic efficiency, an AHU coupled with an enthalpy air to air heat exchanger was investigated energetically by Kalbasi et al. [192]. Engineering Equation Solver program was used to solve the energy balance equations, heating coil, cooling coil, and the mixed box of the system. The enthalpy technic reduced AHU power by recovering more energy in humid and hot climates than in dry and clod ones. Thus, the results present a reduction in cooling coil of 28.3 %, increasing efficiency of the first law by 33 %.

2.16. Summary of chapter

This chapter has explored the key concepts, and empirical studies related to the implementation of EAHE in both residential and non-residential buildings. The key points extracted from this chapter include:

- Length of the pipe EAHE should be at least 20m.
- Diameter of the pipe EAHE should be between 0.2 m and 0.3 m.
- The burial depth of the system installation can be 2 m to 3 m.
- The airflow rate should be between 1 m/s and 3 m/s, which is a good compromise between the pressure drop and heat exchange.
- EAHE may be utilized in both independent and/or combined frameworks, however, standalone EAHE systems are fundamentally limited, whereas coupling EAHE with air-handling systems significantly enhances energy efficiency, operational reliability, and thermal comfort.

The conclusion indicates that additional investigation is necessary to establish dependable design guidelines for various climates, typology and scale of the building and configurations of EAHE. Moreover, the analyses have highlighted and pinpointed notable deficiencies in the current literature, especially regarding the application of hybrid HVAC systems connected to EAHE for minimizing the energy requirements of school buildings while maintaining indoor thermal comfort. The identified gaps underscore the necessity for this study.

The following chapter presents the research methodology, elaborating on the approach employed to address these gaps and fulfil the study's objectives.

CHAPTER 3

RESEARCH METHODOLOGY

3.1. Overview

This chapter outlines the methodological framework adopted to evaluate the thermal energy performance of the proposed hybrid system. Defining the research approach and providing an overview of the study area and methods used to analyse the acquired data are the goals of this chapter. First, a comprehensive literature review was conducted to highlight existing knowledge gaps and set the fundamental theories of the investigation. Based on that, a numerical model relying on mass and energy balance equations applied to moist air is used. This methodology integrates climatic aspect based on Köppen classification, thermodynamic modelling, and performance evaluation to measure the impact of the EAHE on decreasing the design heating and cooling demands of the AHU. A description of the selected building's HVAC setup is provided in detail, including AHU components, fan coil terminals and the integration design with the EAHE.

3.2. Research technique

The present research is based on mathematical calculations and adopted simulation approach to evaluate the amount of power saving achieved through the utilisation of a hybrid air conditioning technology composed from EAHE positioned upstream of an AHU. The analysis is based on energy and mass conservation applied to moist air processes within the AHU heating and cooling coils, especially with regard to heat exchangers. Air thermodynamic properties at the exit of the EAHE are used as input data for the AHU calculations. Sensitive analyses are then conducted to investigate the design parameters effect of EAHE on the resulting power reduction.

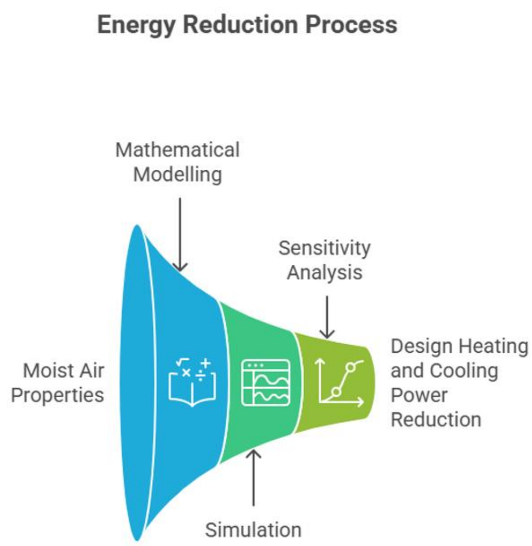


Figure 13. Research Methodology diagram (Source: Author's idea, developed by Napkin)

3.3. Case study description

3.3.1. Building Characteristics

The case study focuses on an existing school building located in Naples, Southern Italy, at coordinates 40° 50′ 49.20″ N latitude and 14° 15′ 54.00″ E longitude. This area is classified under zone C (mild temperate climates) according to the Italian climatic zone classification (DPR 412/93 [193]). The total floor area of the school establishment is about 1534 m^2, with an interior height of 3.3 m and two levels above the ground. The studied educational facility functions as an early childhood centre catering to children between the ages of 3 and 5 years. It accommodates 347 person and includes 7 classrooms with other extra rooms, all described in Table 6 in terms of area, volume and number of occupants in each room. The school operates from 8:30 a.m. to 2:30 p.m. on regular school days during the academic year from September to June. Figure 14 presents the architectural plan, illustrating the intended use of each area while Figure 15 depicting 3D view of the case study building.

Table 6.Detailed description of the building space areas [194].

Space	Area (m^2)	Occupant's Number	Volume (m^3)
Class 1	143.30	36	472.9
Class 2	137.36	34	453.3
Class 3	137.36	34	453.3
Class 4	137.36	34	453.3
Class 5	137.36	34	453.3
Class 6	136.70	34	451.1
Class 7	140.67	35	464.2
Canteen	109.88	53	362.6
Boardroom	24.61	6	81.2
Hallway	271.36	25	895.5
Relaxing area	37.09	8	122.4
Office 1	36.64	4	120.9
Office 2	20.85	2	68.8
Office 3	22.64	2	74.7
Medical room	13.58	2	44.8
Kitchen	17.42	2	57.5

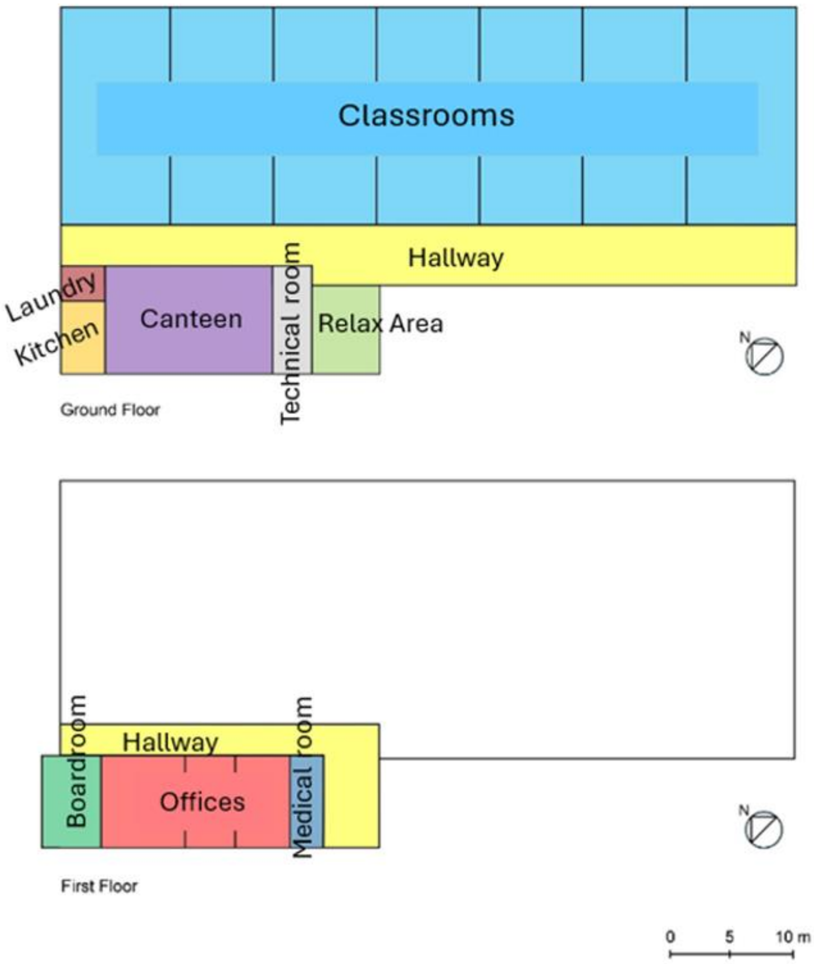


Figure 14. Detailed design of the case study building [194]

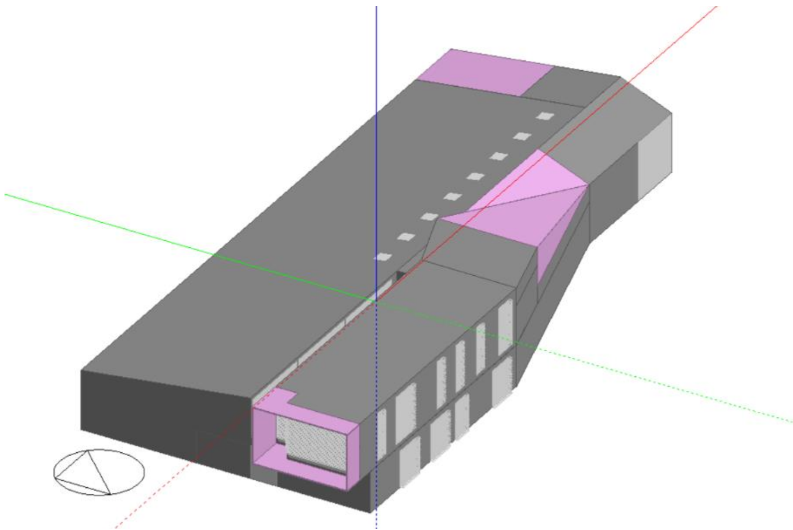


Figure 15. Three-dimensional depiction of the school's architectural geometry utilized in the case study. (Source: [194] designed via Design builder).

The design of the building envelope constructed in compliance with current Italian regulations regarding energy efficiency in structures. Table 7 presents the thermal transmittance values for both opaque and glazed elements of the building envelope.

Table 7. Building envelope thermal transmittance values [195]

Structural Envelope Component	**Thermal transmittance (U) [W/m²K]**
Floor	0.27
Roof	0.26
Windows	1.70
Wall	0.19

In mechanically ventilated school buildings, the necessary outdoor air flow rate is mostly determined by indoor air quality requirements, and it is therefore related to both the number of occupants and the size of the occupied space. In order to correspond towards European ventilation standards, the approach of calculating total outdoor air flow is determined by equation (3), in accordance with Standard EN 16798-1 [196], which defies the minimum ventilation rate based on the design occupancy and area of the school building criteria. The calculation involves area-based ventilation component, which accounts for pollutant emissions from building materials, and a person-based ventilation component, which accounts for bioeffluents generated by occupants (refer to Table 8), which are subsequently summed to obtain a total airflow rate.

$$\dot{V} = Q_B * A + Q_P * N \qquad (3)$$

Where A is the total area of the school building in m^2 and N is the total number of school occupants.

Table 8. Design ventilation rates for individual ventilation rates and the dilution of indoor air pollutants based on EN 16798-1 Standard [2].

Rate of ventilation for emissions from buildings [l/s·m²] (Q_B)	**Rate of ventilation per occupant [l/s per person] (Q_P)**
0.35	/
/	7

3.3.2. Climatic classification and conditions

Weather pertains to the daily variations in temperature and precipitation, while climate describes the mean atmospheric conditions observed over extended time frames [197]. Weather conditions significantly influence energy usage in buildings. It is essential to establish the appropriate boundary conditions regarding the various parameters that impact energy and comfort in buildings, as these may vary from one situation to another based on the specific issue at hand. Considering both macro-climatic context alongside the detailed design specification is crucial for precise modelling of the EAHE and its incorporation into the HVAC system.

3.3.2.1. Köppen climate classification

The classification of climate has a rich history that traces back to ancient Greek scientists and philosophers. However, it was the German scientist Wladimir Koppen (1846–1940) who introduced the first quantitative classification of global climates in 1900 [198]. Climate classification by Köppen can help create better climate change measurements and improve species distribution models (SDMs) because it describes regional climates in a way that is more connected to the environment. This climate classification scheme offers a systematic approach to characterize climatic conditions based on various variables and their seasonal patterns using a unified metric. In contrast to a single variable method, the Köppen classification introduces an additional layer to the understanding of climate variation [199].

Köppen climate classification is determined by the amount and distribution of rainfall, along with changes in temperature throughout the year (monthly/annual) after realizing that plants are indicators for many climatic elements [200]. Climate types are mainly classified based on precipitation and temperature data. The Köppen classification divides Earth's climate into five main types: A, B, C, D, E and H. Type A: climates are based on seasonal rainfall patterns, type B: climates are classified by dryness, types C, D, and E are determined mainly by temperature (C: Temperate/mesothermal climates, D: Continental/microthermal climate, E: Polar climates) while H: Alpine climates (Figure 1). In recent years, an increasing amount of literature has emerged that utilizes the Köppen classification scheme to explore the alterations in the distribution of climatic conditions [201].

The chosen locations are categorized under different climatic zones based on HDD classification and the climate classification proposed by Köppen. Naples is sub-classified as **Csa** (hot-summer Mediterranean climate) according to Köppen classification [199], with **C** refers to *Temperate climate*, **s** is for *Dry summer* and **a** for *Hot summer.* Along with mean monthly temperature of at least 22 °C in the warmest month, while the mean monthly temperature of the coldest month varies between 0 °C and 18 °C. It has approximately 1034 heating degree days [202].

The climate of Hungary is classified as temperate, positioned at the intersection of continental, oceanic, and Mediterranean climatic influences. Within the Köppen–Geiger climate classification framework, Budapest has historically been classified as humid continental Dfa, particularly in datasets extending through the early 2010s [203]. With **D** referring to Continental (snow) climate defined by a coldest month mean temperature below −3 °C following the Köppen–Geiger definition used by Beck et al. [203] or 0 °C, depending on the Köppen threshold adopted like Peel et al. studies [204], **f** denotes a fully humid environment, and a represents **a** warm to hot summer, with the warmest month exceeding 22 °C and at least four months averaging above 10 °C [203].

Despite this historical **Dfa** designation, Budapest has consistently shown transitional climatic features, showcasing the interaction between Atlantic air masses and the growing influence of Mediterranean advection. Recent high resolution monitoring datasets and climate projections reveal that warming trends in Central Europe are gradually pushing the region away from its traditional continental thermal regimes. According to the University of Vianna reports regarding the projected climate shifts and updated Köppen–Geiger climate classification maps [205], [206], vast parts of Hungary, including Budapest shift toward **Cfa** (humid subtropical climate) between the late 20th century (1976–2000) and the end of the 21st century (2071–2100) under medium and high emissions scenarios (SSP2-4.5, SSP5-8.5).

During the past 30 years (1991–2020), monthly mean air temperatures in Budapest have ranged from −3.4 °C in January to 26.6 °C in July to August, while the mean annual air temperature was 12.2 °C [207]. Where these values increasingly consistent with the thermal criteria of the **Cfa** climate type. This warming trend carries significant consequences for building energy demand and the need for seasonal heating. In Hungary, the official heating season runs from 15 September to 15 May of the next year [77], yet it is anticipated that increasing temperatures will gradually reduce the effective heating durations in urban locales like Budapest. Further, the annual total of HDDs in Hungary reached 2344, derived from the average during the climatic period of 1991-2020 according to Bokros and Lakatos [208].

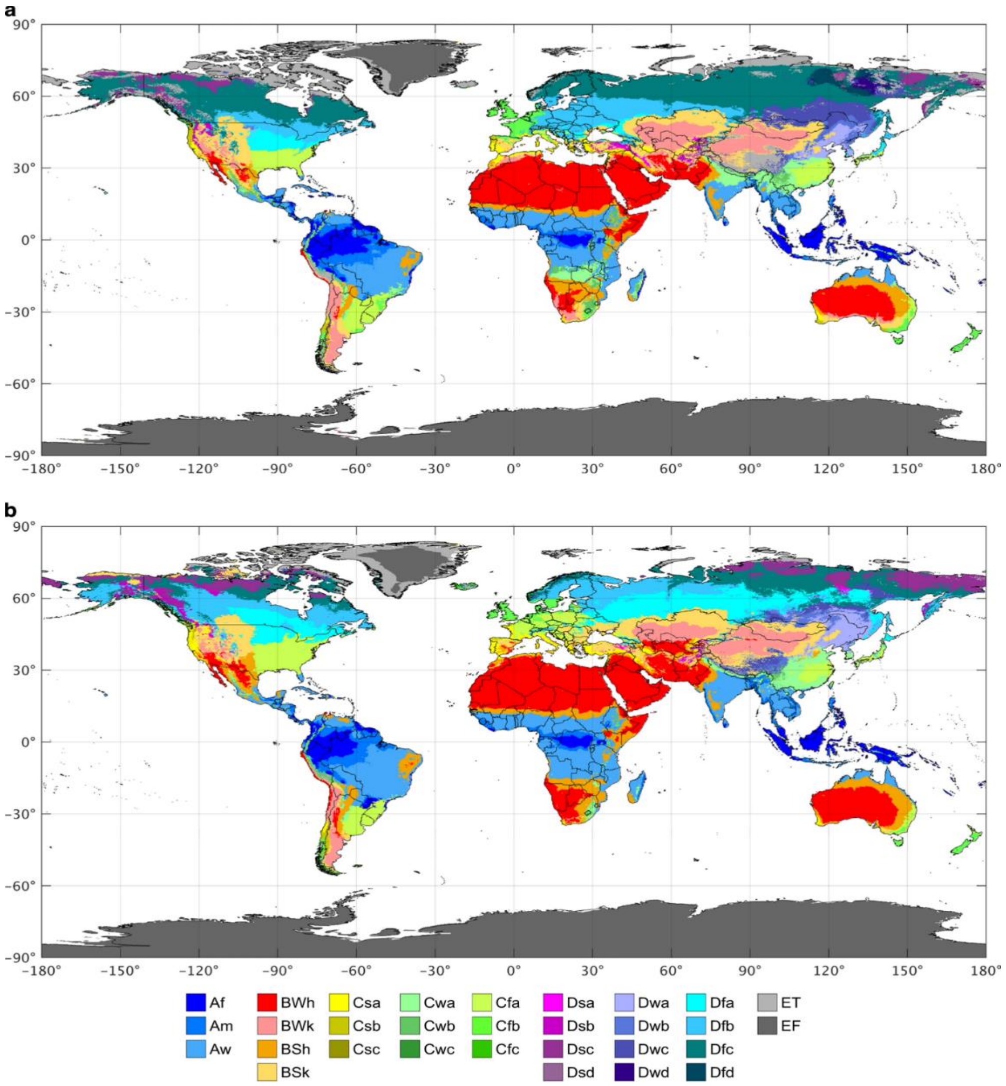


Figure 16. World map based on Köppen climate classification: (a) illustrates the map from 1980 to 2016, while (b) presents the projected map for the years 2071 to 2100. The colour scheme was adopted from Peel et al. [204].

3.3.2.2. HVAC design climatic conditions

The temperature in classrooms is a significant factor in ensuring human comfort. Consequently, there exist three national policies that establish requirements or recommendations regarding the indoor temperature regulated by various systems within school buildings in Hungary. Based on EN 16798-1:2019 indoor temperature of a school classrooms should be maintained throughout the year according to the to the season and the external air temperature. It ranges between 20 and 26°C. The temperature must be regulated for both heating (maintaining a range of 20 - 24°C) and cooling (keeping within 23 to 26°C) [209], [210], [211]. These recommendations work for almost all the European countries like Hungary [24]. The *American society of heating, refrigerating and air-conditioning engineers* (ASHRAE) suggests a 99.6% and 99% annual average probability of occurrence for outdoor dry bulb temperature in cold and warm conditions and based on this reference the external design conditions for the selected European locations are the following:

A. Winter design conditions

The maximum power needed to heat the building named as *'heat load'* is often performed in steady state conditions. That can be calculated according to the basis method of the EN 12831-1 [212] using a constant inside air temperature, outside air temperature (coldest day), absence of solar radiation and internal gains. These represent the essential conditions that can be fulfilled. The relative humidity is typically variable; however, it is advisable to maintain a limit of 65% to prevent issues related to condensation. Regarding that, in the current research the winter design conditions related to the two European locations used in the study are presented in Table 9 according to 99% occurrence based on ASHRAE handbook [213].

Table 9. Winter design condition for the external and indoor air [213].

Winter design conditions	Budapest		Naples	
	Temperature	Relative humidity	Temperature	Relative humidity
	[°C]	[%]	[°C]	[%]
Outdoor air condition	-9.1	65	2.3	55
Indoor air condition	20	50	20	50

B. Summer design condition

Generally, there is no requirement to implement a cooling system, whereas heating is typically a necessity across Europe. During a *summer design day*, clear sky conditions in July are typically regarded as the most critical scenario, and the hottest average outdoor temperatures should be taken into account. A cooling system is designed to uphold specific comfort conditions within the rooms, typically around 26°C. In this scenario, the cooling system must be appropriately sized to achieve the specified objective. Relative humidity is typically set at 50%, though it may be adjusted slightly higher if maintaining a constant level proves to be prohibitively expensive, such as in residential buildings. In this research, the summer design condition of humid air supplied to the educational building (non-residential) based on 99%

occurrence of ASHRAE handbook [213] are reported in Table 10. ($T_{summer\ design}$). For Budapest it ranges between 33°C and 31.1°C based on ASHRAE. According to that, in the study an outdoor air temperature of 32 °C is selected.

Table 10. Summer design conditions for the external and indoor humid air at the school building [213].

Summer design conditions	Budapest		Naples	
	Temperature	Relative humidity	Temperature	Relative humidity
	[°C]	[%]	[°C]	[%]
Outdoor air condition	32	46.7	31.8	50
Indoor air condition	26	50	26	50

3.4. Description of EAHE–AHU hybrid system configuration

3.4.1. EAHE design

The modelling framework of the outdoor pre-conditioning facilitates the analyses of the system across various scenarios, including several EAHE pipe geometries in terms of lengths (20, 40, 60, 80 and 100 m) and diameters (0.5, 0.3 and 0.2 m), in addition to seasonal operating modes. The properties of the outlet air from the EAHE serves as boundary conditions for the inlet of AHU. To guarantee significant power saving, the air is pre-treated by an EAHE placed upstream AHU. In order to determine the required thermal capacity needed to reach the desire indoor temperature and relative humidity, the AHU heating and cooling coils are modelled using steady-state energy balance equations.

3.4.1.1. Soil temperature modelling

In this study, by changing the ground temperature value using Kusuda-Achenbach equation (4) to suit the research location, 2D mathematical model of an EAHE was adopted from validated numerical studies found in the literature [214], [215].

Kusuda-Achenbach equation is used to calculate the undisturbed soil temperature at depth x and time t:

$$T_g(x,t) = T_m - A \cdot e^{\left(-x\cdot\sqrt{\frac{\pi}{P\cdot a}}\right)} \cdot \cos\left[\frac{2\pi}{P} \cdot \left(t - t_{min} - \frac{x}{2} \cdot \sqrt{\frac{P}{\pi a}}\right)\right] \quad (4)$$

Where $T_g(x,t)$ in °C is ground temperature at depth x [m] and time t [s], T_m is the average annual soil surface temperature [°C], equal to 10°C for Budapest and 18 °C for Naples in the analysed case, A is amplitude of soil surface temperature fluctuations [°C], equal to 12 °C in Budapest and 8.5 °C in Naples in the analysed case, a is thermal diffusivity of the ground [m^2/day], P is the analysis period (typically 365 days), is t_{min} refers to day of minimum surface temperature (the phase shift) [days], equal to 21 days in Budapest and 15 days in Naples in the analysed case.

In this study, the researchers assumed that the soil is homogeneous and isotropic in both cites (Budapest and Naples) with the reason to simplify the thermal analysis. Consequently, identical thermos-physical soil parameters were used for both locations. The thermal diffusivity of the ground α [m^2/s] is calculated as follows:

$$\alpha = \frac{\lambda}{\rho c_p} \quad (5)$$

Where λ is the thermal conductivity of the ground [W/m^2K)] and taken as 2.20 W. m^{-1}. K^{-1}, ρ denotes density of the ground [kg/m^3], equal to 2500 kg. m^{-3} and $c_p$is specific heat capacity of the ground [J/ (kg. K)] which is assumed to be 900 J kg^{-1} K^{-1}. The use of these properties [216] allows to estimate the undisturbed ground temperature using the Kusuda–Achenbach model. The soil temperature profiles were then shown next to the EAHE outlet air temperature in the next chapter to illustrate the thermal interaction potential between the ground and the ventilating air. It is acknowledged that practical soils properties vary with composition, moisture content and depth; in the present analysis, these influences were neglected in order to maintain consistency with the assumptions of Kusuda model.

3.4.2. AHU configuration

A conventional and baseline AHU system where the EAHE is not linked (Figure 17) is compared against a new hybrid EAHE-AHU configuration (Figure 18) to quantify performance differences. The hybrid HVAC system functions within an open-loop configuration. The AHU provides the renewal of the indoor air, ensuring optimal air quality within the building environment. According to Eq. (6), the EAHE system consists of 40 horizontally embedded pipes arranged in parallel, positioned at a depth of 2.5 meters below ground level.

$$N_{pipe} = \frac{\dot{V}}{V_{pipe}} \quad (6)$$

Where N_{pipe} is the number of pipe, $\dot{V}$ is the total air flow rate and V_{pipe} is the air flow rate within a single EAHE pipe equal to 269 m^3/h.

The air flow rate is maintained at a constant level to achieve the intended design air change rate of the school building, resulting in varying air velocities within the EAHE pipes. The system was under three different air velocities which are calculated according to the following equation:

$$\text{v} = (V_{pipe}/(3.14 * ((\frac{D}{2})\text{^}2))) \quad (7)$$

Where V_{pipe} is the air flow rate within a single EAHE pipe equal to 0.075 m^3/s and D denotes pipe diameter in m. This research approach provides insights of optimization and the utilisation of such hybrid systems in school building.

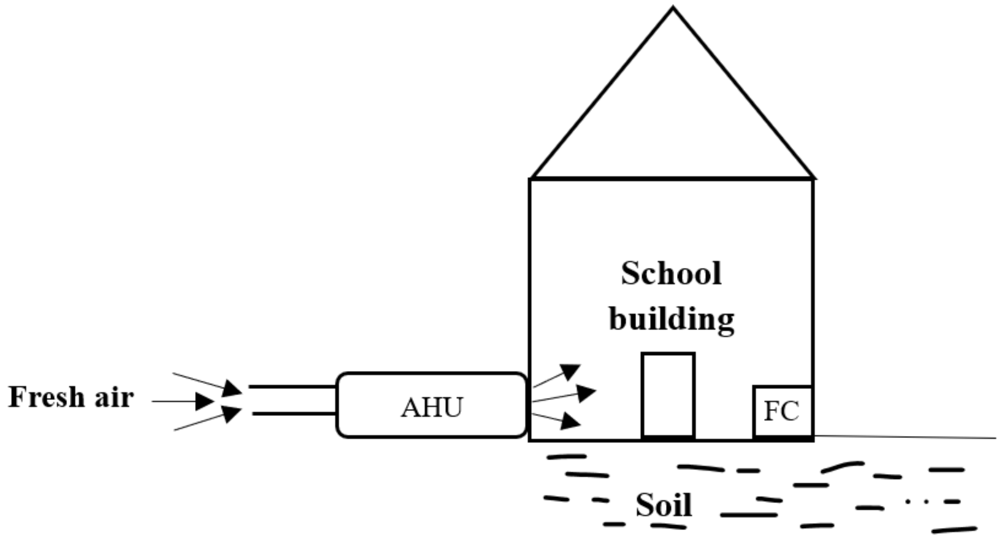


Figure 17. A basic setup of the existing HVAC system (AHU + fan-coils FCs)

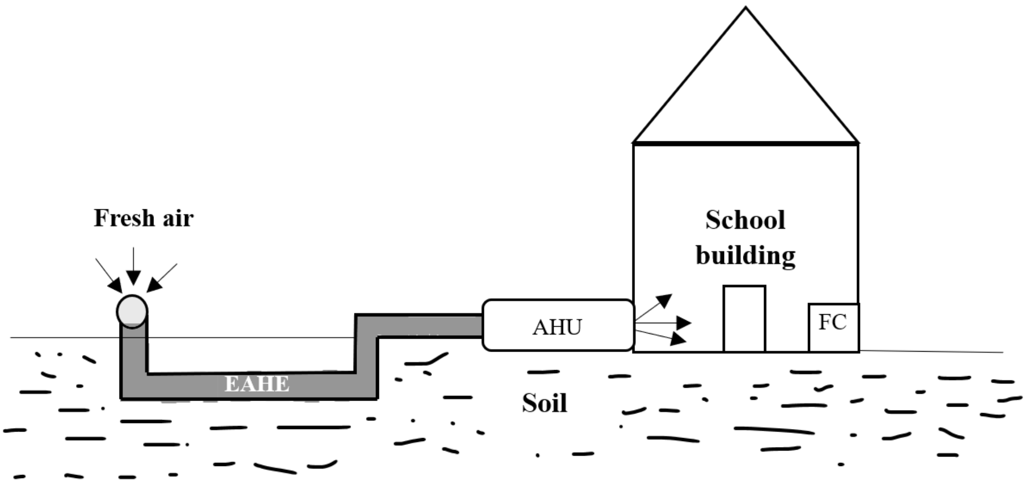


Figure 18. The suggested layout of a hybrid EAHE-AHU system with fan coils (FCs)

3.4.3. HVAC setup

The HVAC system mainly consists of an Air Handling Unit along with circular air ducts for the distribution of primary air, hydronic fan-coils for both heating and cooling, and heat pumps serving as the generators for heating and cooling processes. The two reversible electric air-to-water heat pumps have a combined nominal power rating of 120 kW for heating and 160 kW for cooling. The AHU functions incessantly throughout occupancy hours. The distribution of water is facilitated through insulated copper ducts integrated within the building's framework. The production of domestic hot water (DHW) is achieved through the utilization of an appropriate electric air-to-water heat pump. According to the new Hungarian regulatory requirements [217], the operational duration of the heating system in Budapest runs for 10 hours each day, commencing on the 15th of September and concluding on the 15th of May. In contrast, the cooling system functions for four hours daily, specifically from mid-June through July. While, in Naples based on Italian regulatory obligations [218] the system is active for heating from 15th November to 31st March for 8 hours per day, and it is operative for cooling from June to July for 6 hours per day. All three basic systems - primary air, cooling/heating, and DHW are detailed in Table 11.

Table 11. Key features of primary air, cooling/heating, and domestic hot water systems [194].

System		Value
Primary air	Supply outdoor air flow rate	10692 [m^3/h]
	Air Handling Unit with hydronic coils	
	Fan power	Min 2.1 Max 2.2 [kW]
Domestic Hot Water	System type:	
	300 L tank and electrical air-to-water heat pump	
	Power	12 [kW]
	Efficiency of the distribution	0.9
	COP	3.5
Cooling/Heating	System type: hydronic fan coil	
	Total cooling/heating capacity	160/120 [kW]
	Efficiency of the distribution	0.9
	Heat pump COP/EER	3.8/4.2
	Efficiency of the emission	0.9

3.5. Transformation of Humid Air

3.5.1. Psychrometric Properties of Humid Air

The interaction between dry air and water vapor results in a humid air mixture. It is crucial in ventilation and air conditioning applications to quantify the changes in latent and sensible thermal energy of the air and to evaluate the indoor thermal comfort condition through the assessment of the properties of humid air. The thermodynamic state of humid air can be sufficiently described using a limited set of independent variables. In this research, the presented psychrometric analysis is based on four fundamental properties: air temperature in °C, humidity ratio (specific humidity) in g/kg, relative humidity in %, and specific enthalpy in kJ/kg. These air properties are calculated with an assumption that the humid air behaves as an ideal gas mixture at constant atmospheric pressure equivalent to 101.325 kPa.

3.5.1.1.Temperature of air

The dry-bulb temperature T (°C) is a primary variable in psychrometric calculations. It represents the sensible thermal state of the air. In this research, the design outdoor air temperature is obtained directly from the ASHRAE handbook [213], while the temperature at the outlet of EAHE is obtained from a validated model [214].

3.5.1.2.Relative humidity

This property (ϕ) represents the degree of saturation of the air in %. It is defined in the study as:

$$\phi = \frac{pv}{pvs} \times 100 \qquad (8)$$

Where p_v is the partial water vapor in kPa and p_{vs} is the saturation vapor pressure of water vapor in kPa both at the same air temperature T (°C). According to Monteith and Unsworth [219], Tetens' formula is to calculate saturation vapor pressure at given temperature $P_{WS}(T)$, for temperatures above 0 °C as:

$$P_{WS}(T)\ [kPa] = P_{WS,0°C} \cdot e^{\left(\frac{aT}{T+b}\right)} \qquad (9)$$

where:

$P_{WS,0°C}$ depict the saturation vapor pressure at 0 °C (0.61078 kPa), T is air temperature [°C], a picture dimensionless constant that sets the slope of the exponential term, equivalent to 17.27 and b show the constant that sets temperature offset in the denominator equivalent to 237.3 °C.

3.5.1.3.Humidity ratio

It also called specific humidity (ω) expresses the moisture content of the air in g/kg which is calculated as:

$$\omega = \varepsilon \cdot \frac{P_V}{P-P_V} \qquad (10)$$

where:

ε is ratio of the molar mass of water-vapor to the molar mass of dry air equal to 0.622 and P is air pressure [kPa] (at sea level equal to 101.325 kPa).

3.5.1.4.Specific enthalpy

The total energy content of the combination air-vapor, including both latent and sensible energy represents the specific enthalpy of humid air (h) in kJ/kg. It is computed in the study as:

$$h = c_{pa} \cdot T + \omega\left(h_{we} + c_{pw} \cdot T\right) \qquad (11)$$

where:

c_{pa} denotes specific heat of dry air at ≈ 1 bar and 0–60 °C (1.006) [kJ/(kg. K)], T is dry bulb temperature [°C], ω represent humidity ratio [kg_{H2O}/kg_{air}], h_{we} is the latent heat of water vaporization at 0 °C, equal to 2501 [kJ/kg] and c_{pw} is the specific heat of water vapor, equal to1.805 [kJ/(kg. K)].

3.6. EAHE thermal and hygrometric performance modelling

This study does not model the thermal behaviour of the Earth Air Heat Exchanger from fundamental concepts. Instead, the EAHE's outlet air temperatures come from models that have been tested and shown to be accurate in the literature [214]. This technique enables the current study to concentrate on assessing the influence of EAHE integration on the performance of the Air Handling Unit, rather than on the detailed numerical modelling of the EAHE itself.

Consequently, the EAHE outlet air temperature and humidity values used in this investigation are regarded as input data, reflecting the outcome of ground–air heat exchange inside the underground pipes. These adopted EAHE outlet temperatures are then used to evaluate the pre-conditioning results of the EAHE on the ventilation air before it enters the AHU.

Although the EAHE thermal model has not been explicitly defined; hygrometric variations within the EAHE are accounted for, particularly the potential condensation of water vapor on the inner surface of the pipes. When placing EAHE upstream the AHU to pre- condition outside air, along the buried pipes both hygrometric and thermal transformations may occur. During summer operation, the incoming air featured a high temperature and moister content. As the air flow and pass through EAHE, sensible heat transfer to the surrounding soil, leading to thermal transformation corresponds to progressive reduction in air temperature. In addition, as the incoming air cools and once saturation conditions are reached, a hygrometric transformation may happen. The last transformation characterized by condensation of water vapour on the inner surfaces of the pipes and a decrease in specific humidity. The mass of condensed water in the EAHE is determined by a moisture mass balance represented as (Eq.12):

$$\dot{m}_{cond} = \dot{m}_a \, (\omega_O - \omega_E) \quad (12)$$

With dry air mass flow rate denotes as $\dot{m}_a$, ω_O and ω_E represent the specific humidity of the air at the inlet (outdoor air) and outlet EAHE, respectively.

3.7. AHU heating and cooling coil load calculation

3.7.1. Definition of air states in the system

For the purpose of clarity in the analysis, this study defines three distinct air conditions as it is illustrated in Figure 19.

- **Inlet air** refers to the outdoor ambient air entering the Earth–Air Heat Exchanger (EAHE), representing the initial boundary condition of the system.
- **Outlet air** is the air leaving the EAHE system after the heat exchanger process with the surrounding soil. This air is pre-conditioned before entering the Air Handling Unit (AHU).
- **Supply air** indicates the conditioned air delivered to the indoor space after being treated by the AHU, meeting the required thermal comfort conditions in terms of temperature and humidity.

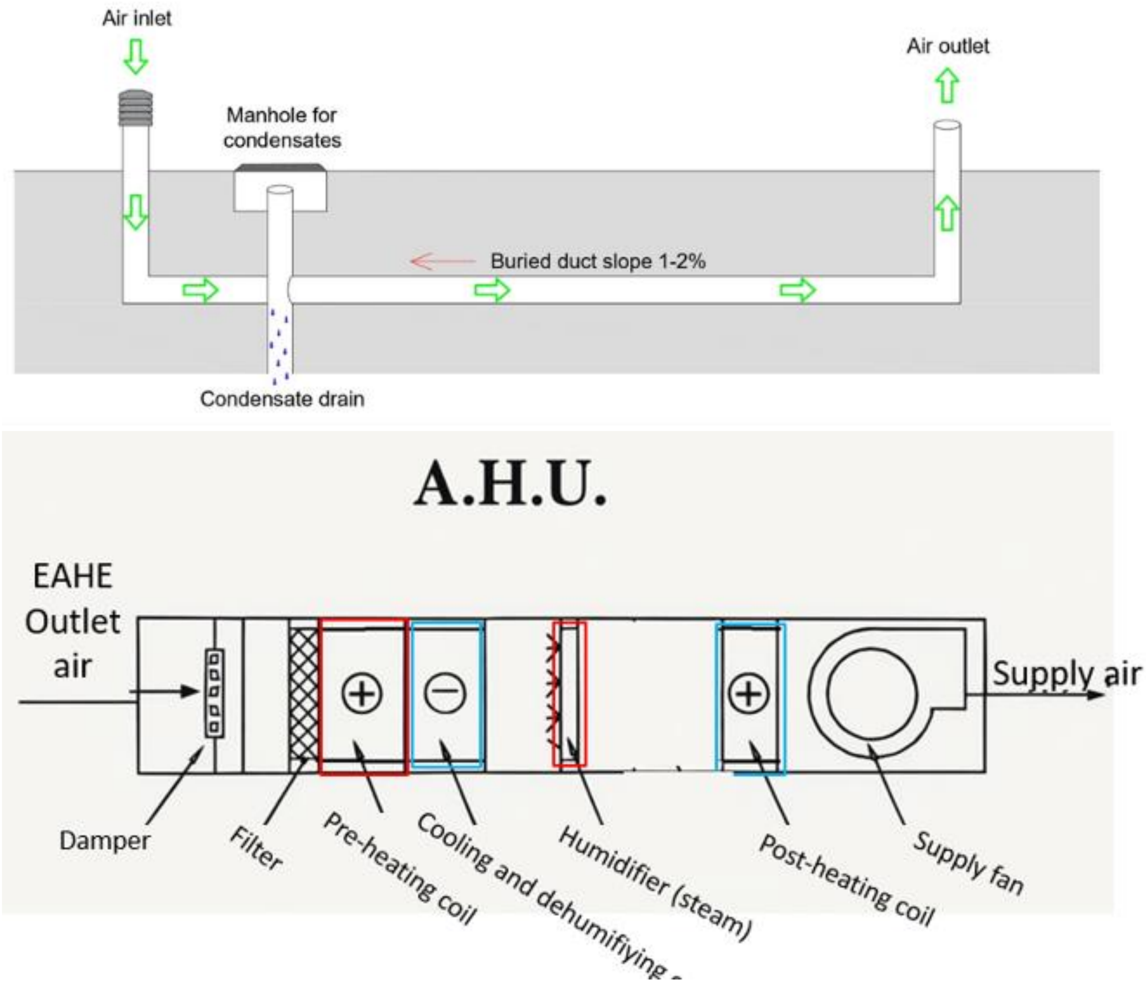


Figure 19. Details EAHE-AHU system

To ensure optimal thermal comfort for the building's occupants during working hours and to meet the internal thermo-hygrometric design conditions, a supply air setpoint temperature of 13°C in summer and 20°C in winter has been selected. The humidity ratio values ω_s of the supply air for the air-conditioned rooms, derived from the mass balance equation (Eq.13-15), are estimated to be 8.7 g/kg in summer and 6.38 g/kg in winter. Subsequently, utilizing the psychrometric chart, the relative humidity values are determined to be 92.95% for summer and 43.42% for winter. Additionally, the indoor air temperature setpoints are established at 20°C during winter and 26°C in summer, with a consistent relative humidity (ϕ) of 50%.

$$\dot{m}_a = \frac{\dot{V}}{\vartheta i} \quad (13)$$

$$\dot{m}_a \omega_s + \dot{m}_v = \dot{m}_a \omega_r \quad (14)$$

$$\omega_s = \omega_r - \frac{\dot{m}_v}{\dot{m}_a} \quad (15) \text{ with } \dot{m}_v = \dot{m}_{v,occ} \times N \quad (16)$$

Where air mass flow rate is represented with $\dot{m}_a$, total vapor mass flow rate of the occupant denotes as $\dot{m}_v$ and ω_r indicates the humidity ratio value of the air to be determined in the rooms, $\dot{m}_{v,occ}$ is for mass vapour per person and N represents the total number of individuals present in the school.

Tables 12 and 13 present the characteristics of the air under specified conditions: design outdoor air conditions corresponding to a 99% occurrence as outlined in the ASHRAE handbook [213], supply air conditions and air conditions subsequent to the cooling or heating coil in the AHU.

Table 12. Properties of humid air within the fundamental HVAC system under winter design conditions.

	Budapest				**Naples**			
	T	Φ	ω	h	T	Φ	ω	h
	[°C]	[%]	[g/kg]	[kJ/kg]	[°C]	[%]	[g/kg]	[kJ/kg]
Design outdoor air conditions	-9.1	65	1.23	-6.11	2.3	55	2.45	8.46
Air conditions after the heating coil in the AHU	20	8.53	1.23	23.23	20	16.96	2.45	26.32[
Supply air conditions	20	43.42	6.38	36.31	20	43.42	6.38	36.31

Table 13. Properties of humid air within the fundamental HVAC system under summer design conditions.

	Budapest				**Naples**			
	T	Φ	ω	h	T	Φ	ω	h
	[°C]	[%]	[g/kg]	[kJ/kg]	[°C]	[%]	[g/kg]	[kJ/kg]
Design outdoor air conditions	32	46.7	14	68.01	31.8	50	14.8	69.96
Air conditions after the cooling coil in the AHU	11.9	100	8.7	33.91	11.9	100	8.7	33.91
Supply air conditions	13	92.95	8.7	35.03	13	92.95	8.7	35.03

In a standard air-water HVAC configurations, the active elements of the air handling unit include filters, a blower (supply fan), a hydronic heating coil and vapor humidifier for winter, a hydronic cooling and dehumidification coil along with a re-heating coil for summer. Figures 20 and 21 illustrate on the psychrometric chart, the humid air processes occurring in the AHU. During the winter, with the aim of reaching the required setpoint for the supply primary air (T_{ba}=20 °C; ω=6.38 $g \cdot kg^{-1}$), heating from point ``O`` to point ``A`` plus vapor humidification from point ``A`` to point ``S`` are the processes used which aligns with the thermohydrometric conditions that should be upheld in the room (point “r”). During the summer and with the aim of reaching the required setpoint for the supply primary air (T_{ba}=13 °C; ω=8.7 $g \cdot kg^{-1}$), cooling and dehumidification from point ``O`` to point ``A`` plus re-heating from point ``A`` to ``S`` are the processes used to maintain the thermohydrometric conditions in the room (point “r”).

When the EAHE is utilized for pre-heating/pre-cooling the air flow, the point “O” (outside air) is replaced with the point “E” (air conditions at the exit of the EAHE), identified through the 2D model derived from existing studies [214].

The chart indicates that point ‘O’ corresponds to the design outdoor air conditions, point ‘E’ represents the air conditions at the EAHE outlet, point ‘S’ denotes the supply air conditions, and point ‘r’ signifies the design indoor conditions necessary for ensuring thermal comfort. $T_{outdoor}$ represents the external air temperature, T_{EAHE} denotes the air temperature at the EAHE outlet, and T_{supply} indicates supply primary air temperature.

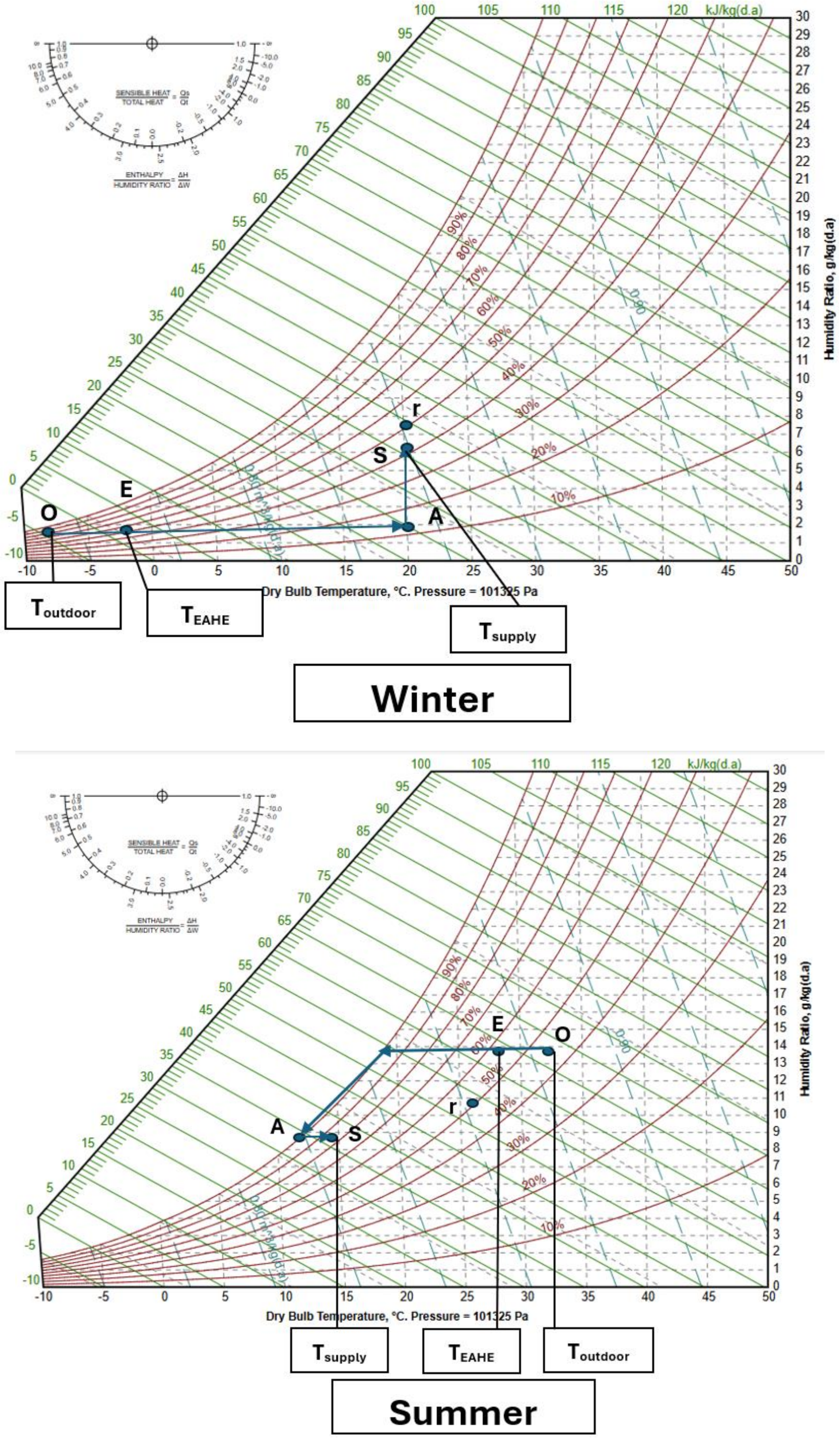


Figure 20. Representation on the psychrometric chart of the humid air treatment processes in the air handling unit for heating and cooling modes in Budapest

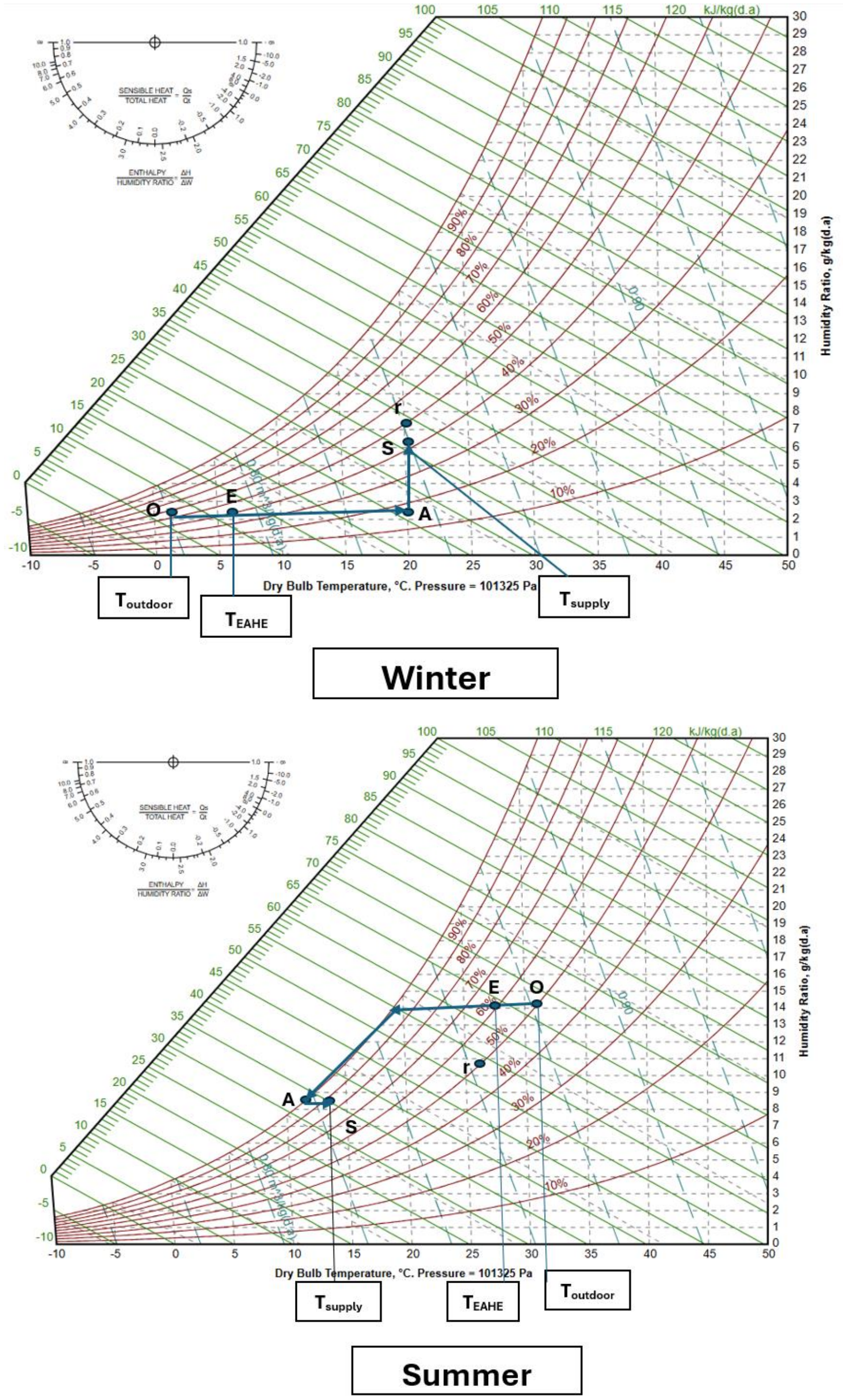


Figure 21. Representation on the psychrometric chart of the humid air treatment processes in the air handling unit for heating and cooling modes in Naples

3.7.2. Baseline AHU load

In order to evaluate the capacity of the coils, calculations involving mass and energy balances are conducted within a defined control volume. During the summer months, both the cooling coil and the re-heating coil are operational. The equation (17) represents the energy balance utilized for determining the design cooling capacity in the fundamental configuration, excluding EAHE:

$$\dot{Q}_{cc} = \dot{m}_a(h_o - h_A) - \dot{m}_{a,co}h_{co} \quad (17)$$

In this context, Q_{cc} represents the design capacity of the cooling coil measured in kW. The variable m_a denotes the air mass flow rate in kg/s. The specific enthalpy values, h_O and h_A, are expressed in kJ/kg for the outdoor air and the air post-cooling and dehumidification process, respectively. Additionally, $m_{a,co}$ indicates the condensed water mass flow in kg/s, while h_{co} refers to the specific enthalpy of the condensed water in kJ/kg.

The re-heating coil capacity can be calculated through (Eq. 18):

$$\dot{Q}_{ReH} = \dot{m}_a c_p(T_s - T_A) \quad (18)$$

With $\dot{Q}_{ReH}$ is the re-heating process capacity in kW, c_p represent the specific heat of humid air, quantified as 1.006 kJ/(kg. K), while T_s and T_A refer to the temperatures in °C of the supply air and the air post-cooling and dehumidification process, respectively.

During the winter, as the active components are the heating coil and vapor humidifier, the design heating capacity is calculated (in the basic configuration without EAHE) based on the subsequent energy balance (Eq. 19):

$$\dot{Q}_{He} = \dot{m}_a(h_A - h_o) \quad (19)$$

$\dot{Q}_{He}$ represents the design capacity of the heating coil in kW, whereas h_o and h_A denote the enthalpy in kJ/kg of the outside air and the air after the heating process, respectively.

3.7.3. AHU load with EAHE pre-conditioning system

For calculating the cooling and heating coil capacity when the EAHE is integrated before the AHU the same equation (17) and (19) are used by replacing the specific enthalpy of the outdoor air (h_o) with the specific enthalpy of the air at the exit of the EAHE. Thus, in the evaluation of the EAHE, it is observed that the capacity of the AHU coils is diminished during both summer and winter, as detailed in the next chapter.

The heat transfer capacity of the processed air stream within EAHE is computed using equation (20) by taking into account the inlet and outlet temperatures while the fan power (W_{fan}) needed to deliver the outdoor air into the EAHE-AHU hybrid system is determined by equation (21):

$$Q_{EAHE} = \dot{m}_a(h_{a,in} - h_{a,out}) \quad (20)$$

where Q_{EAHE} is the heating capacity of the EAHE system in kW; $h_{a,in}$ is the specific enthalpy of air entering the EAHE system in kJ/kg and $h_{a,out}$ is the specific enthalpy of air at the outlet of EAHE in kJ/kg.

$$W_{fan} = \frac{\dot{V} * \Delta p}{\eta_{fan}} \quad (21)$$

Where V is the total air flow mass in m^3/s; Δp is the pressure drop of the EAHE-AHU system in Pa and η_{fan} is the efficiency of the blower (fan).

An essential performance metric for EAHE is the Coefficient of Performance (COP), which serves as an indicator of a heating or cooling system's effectiveness, reflecting the ratio of useful heating or cooling provided to the energy consumed. Consequently, the calculation of COP can be performed using Equation (22):

$$COP = \frac{Q_{EAHE}}{W_{fan}} \quad (22)$$

where Q_{EAHE} is the heating capacity of EAHE system in kW and W_{fan} is the electric power of the blower in kW.

3.8. Power reduction calculation

Under identical design day condition, the power reduction of AHU was calculated by comparing heating and cooling coil loads with and without EAHE pre-conditioning system using Eq. 23. The resulting thermal load difference represents the contribution of the passive system to peak ventilation power demand.

$$Reduction\ (\%) = \frac{Q_{baseline} - Q_{with\ EAHE}}{Q_{baseline}} * 100 \quad (23)$$

3.9. Chapter summary

This chapter examines the methodology employed to investigate the potential of an Earth–Air Heat Exchanger positioned above an Air Handling Unit in reducing the heating and cooling coil capacities of a school building. The description of the case study, the configuration of the system, and the assumptions made for modelling were all outlined. The ventilation air flow rate was determined according to EN 16798-1, and the thermodynamic properties of humid air were calculated using standard psychrometric relationships. The air conditions at the EAHE exit were taken from the literature, while the amount of moisture that condensed within the EAHE was quantified through changes in humidity ratio. Finally, the steps used to measure AHU design heating and cooling coil loads were explained. This approach provides a consistent basis for the analysis and discussion of results displayed in the following chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Overview

In this chapter, the outcomes and the results of this research derived from the design-day are presented and discussed in relevant with the existing studies on hybrid EAHE-AHU systems. The topic of the discussion is organized around the following key aspects:

- Thermodynamic state of the ventilation air within the EAHE

- The performance of EAHE as a pre-conditioning device on the inlet air conditions of the AHU.

- Reduction in the design heating and cooling coil of the AHU

- The associated peak power demand mitigation

- Comparative efficiency of the proposed hybrid system under winter and summer design conditions.

- Consistency of this study findings with the previous documented studies.

4.2. Computed input parameters and boundary conditions

The key input parameters and boundary conditions that were applied in the numerical evaluation of the EAHE integrated to an AHU are presented in this section. All the variables are obtained from the governing equations outlined in the methodology chapter and reflect the operating conditions where the system performance is measured for the chosen design days (January for winter and July for the summer).

4.2.1. Ventilation flow rate

The required outdoor-air ventilation rate was determined from the building floor area and occupancy using Eq. (3). With Q_B=35 l/s. m^2, A=1534 m^2, Q_P= 7 l/s. person and N=347. The construction-related element then is $\dot{V_B} = Q_B A = 536.86\ l/s$ and the occupant-related component is $\dot{V_P} = Q_p N = 2429\ l/s$,giving a total ventilation rate of $\dot{V} = 2965.86\ l/s$ which is almost 2.97 m^3/s, equivalent to 10692 m^3/h. The airflow rate acted as the reference value for all computations related to EAHE and AHU, ensuring that the mass and energy balances remained consistent throughout the study.

4.2.2. Undisturbed soil temperature at selected depth

The undisturbed ground temperature where the EAHE pipe is buried at depth of 2.5 m serves as the subsurface boundary condition was computed using Kusuda analytical model expressed in Eq. (4). The resulting ground temperature profile remains relatively constant recorded at 12.3°C and 17°C for Budapest and Naples, respectively in relation to the ambient air average yearly temperature. The study assumes that the HVAC system operates in a steady state throughout the design hour in order to maintain consistency with typical HVAC design practices.

4.2.3. Air velocities within EAHE

The air speed inside the EAHE pipes is a dependent variable resulted from the combination of varying pipe diameters and the use of a constant ventilation air flow rate. As expressed by Eq. (7), the air velocity is inversely proportional to the pipe cross-sectional area. Hence, with the same volumetric airflow rate, larger pipe diameters result in a slower air movement, while smaller pipe diameters lead to a faster air movement. For a pipe diameter of 0.5 m, the resulting air velocity was 0.38 m/s. Reducing the diameter to 0.3 m increased the velocity to 1.04 m/s, while a further reduction to 0.2 m led to a velocity of 2.38 m/s.

4.2.4. Design-day climatic characteristics

The findings in this chapter are assessed under representative cooling and heating design-day conditions, reflecting the peak ventilation loads for the examined school building. The circumstances of the outdoor air determine the boundary state at the EAHE and serve as a reference for evaluating the most demanding ventilation scenarios from a size point of view for HVAC.

For the cooling design day, the outside air features high dry-bulb temperature and humidity ratio presented as 32 °C (based on ASHEAR Handbook), 14 g/kg according to Eq. (10) for Budapest and 31.8 °C (based on ASHEAR Handbook), 14.8 g/kg for Naples which causes significant sensible and latent ventilation loads at the input of AHU. Conversely, the heating design day characterized by low external air temperatures equal to -9.1 °C, 1.23 g/kg for Budapest and 2.3 °C, 2.45 g/kg for Naples, which means that the thermal load of the AHU in school building is dominated by heating demand associated to ventilation. These outdoor air conditions are used as baseline for assessing the passive pre-conditioning system.

4.2.5. Air mass flow rate

By applying the specific volume of humid air under at input conditions, the researcher determined the air mass flow rate derived from the total ventilation air flow rate. The specific volume of air, represented as ϑi, considered to be stable and equal to 0.816 m³/kg. Using Eq (13) enable to determine the air mass flow rate as the ratio between the volumetric airflow rate and the specific volume of air.

For a total ventilation flow rate of 10692 m³/h, the corresponding air mass flow rate was calculated as 13103 kg/h, which is equivalent to 3.64 kg/s. This mass flow rate then was adopted as a fixed boundary condition for the thermal analyses of the hybrid system EAHE-AHU.

4.2.6. Determination of supply air humidity ratio

Equation (14) is based on the mass balance concept within the occupied space of the school building, with assumption of constant ventilation rate and occupancy. It is used to define the required humidity ratio of the supply air ω_s through the Eq. (15). For this regard, the ω_r (indoor humidity ratio) was taken directly from the psychrometric chart based on the targeted indoor thermal comfort conditions (20°C for winter and 26°C for summer) with a relative humidity of 50%. This air property was equal to 7.3 g/kg in winter and 10.5 g/kg in summer.

The total water vapor mass flow rate generated indoors was calculated using Eq. (16), considering the vapor emission rate per person ($m_{v,occ}^{\cdot}$) according to the standard UNI 5104 and the entire number of occupants (347 person). The selected $m_{v,occ}^{\cdot}$ were 35g/h in winter and 70g/h in summer (Table 14). The values for internal heat and moisture emission were taken from the Italian standard UNI 5104. However, these values are based on human physiological behaviour during a typical indoor activity level and are in line with what is commonly practice in HVAC and building performance simulation around the world. The metabolic heat and moisture generation of occupants are not significantly dependent on nationality but on activity level which is education in this research and is comparable between Italy and Hungary for classroom case studies [220]. Therefore, the use of UNI 5104 values is appropriate for the purpose of design coil load and ventilation calculations in the selected locations. During winter the total mass vapor per occupants ($\dot{m}_v$) presented as 12145 g/h equivalent to 3.37g/s while during summer it is 24290 g/h equivalent to 6.74 g/s. At this point all the terms are available to computed ω_s and it is equal to 6.38 g/kg and to 8.7 g/kg in winter and summer respectively.

This value was used in the calculation of the AHU heating and cooling coil loads, allowing the impact of EAHE pre-conditioning on the design coil capacity to be assessed.

Table 14. Thermal power and water flow rate released by an individual into the environment as the dry bulb temperature of the air varies based on Standards UNI 5104 [221].

T_{amb} (°C)	$\dot{Q}_T$ (W)	$\dot{Q}_S$ (W)	$\dot{Q}_L$ (W)	$\dot{m}_v$ (g/h)
20	116	93	23	35
21.5	116	87	29	45
22	116	81	35	50
25	116	75	41	60
27	116	64	52	80

In Table 14, $\dot{Q}_T$ demonstrates the complete metabolic heat produced by an individual, which is divided into a sensible component $\dot{Q}_S$ modifying the air temperature and a latent component $\dot{Q}_L$ associated with the emission of moisture, quantified by the corresponding water vapor mass flow rate. These values were used as design assumptions. While the amount of moisture released by occupants can vary, this variation will still be small and limited compared to the uncertainty linked to occupancy schedules and ventilation operation, thus this fluctuation in mass vapor release per person does not significantly affect the finding of supply air humidity ratio (ω_s).

4.3. Thermal performance of the Earth-Air Heta Exchanger

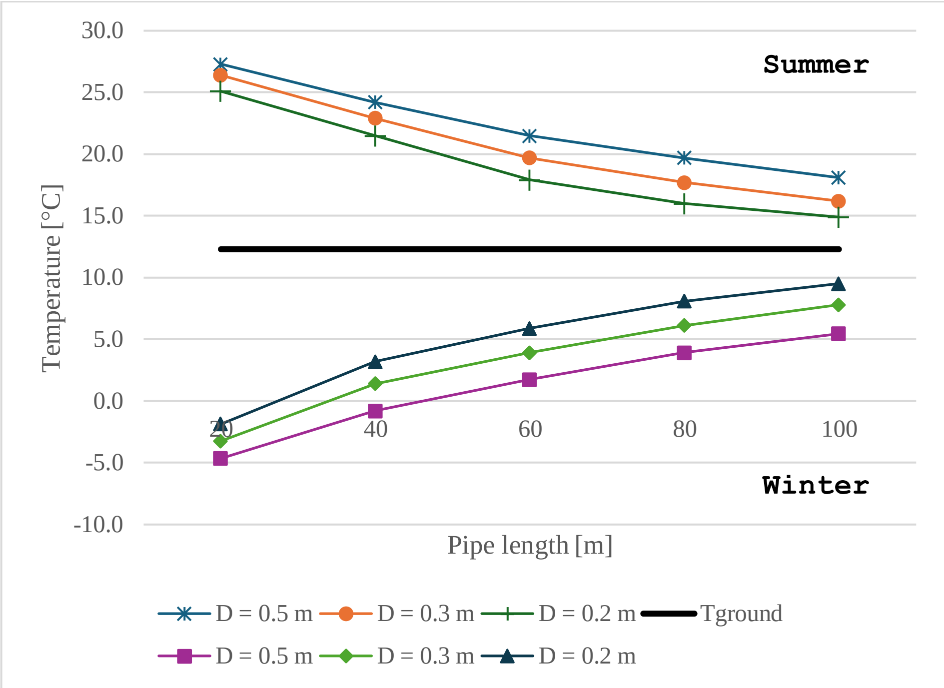
The thermal performance of the EAHE is affected by its geometric configuration, the stable temperature of the soil at burial depth, and the surrounding climatic conditions. In this study, the system performance is focusing on comparing the thermodynamic state of the air in terms of temperature variations at the inlet and the outlet of EAHE system under winter and summer design-day conditions.

According to the adopted modelling approach from the literature [215] the air temperatures at the exist of the EAHE system are reported in Table 15. While graphically, air temperatures along the exchanger, together with the corresponding ground temperature, are presented in Figure 22 for various pipe lengths and diameters in both climates. Under a constant dry air mass flow rate equal to 3.64 kg/s an increment in air velocity from 0.38 to 2.38 m/s occurs when the pipe diameter decreases from 0.5 to 0.2 m, resulting in an enhancement of heat transfer coefficient for convection, which ultimately facilitates heat exchange. This behaviour is consistent with convective heat transfer theory, where higher air velocities increase the internal heat transfer coefficient, thereby improving the overall heat exchange effectiveness between the air and the pipe wall. From an engineering design perspective, this highlights the importance of balancing airflow velocity and pressure losses when selecting pipe dimensions for EAHE systems.

Table 15. Outlet air temperatures (˚C) of the EAHE in Budapest and Naples for winter and summer seasons

Length (m)	**Budapest**					
	Outlet EAHE temperature in winter			Outlet EAHE temperature in summer		
	D = 0.5 m	D = 0.3 m	D = 0.2 m	D = 0.5 m	D = 0.3 m	D = 0.2 m
20	-4.6	-3.2	-1.9	27.3	26.4	25.1
40	-0.8	1.4	3.2	24.2	22.9	21.5
60	1.7	3.9	5.9	21.5	19.7	17.9
80	3.9	6.1	8.1	19.7	17.7	16
100	5.5	7.8	9.5	18.1	16.2	14.9
Length (m)	**Naples**					
	Outlet EAHE temperature in winter			Outlet EAHE temperature in summer		
	D = 0.5 m	D = 0.3 m	D = 0.2 m	D = 0.5 m	D = 0.3 m	D = 0.2 m
20	5.6	6.5	7.5	28.3	27.4	26.6
40	8.5	9.8	11.3	25.6	24	23.2
60	10.2	11.6	13.3	23.9	22	21
80	11.3	12.9	14.3	22.3	20.5	19.6
100	12.5	14	15.2	21.3	19.6	18.7

(a)



(b)

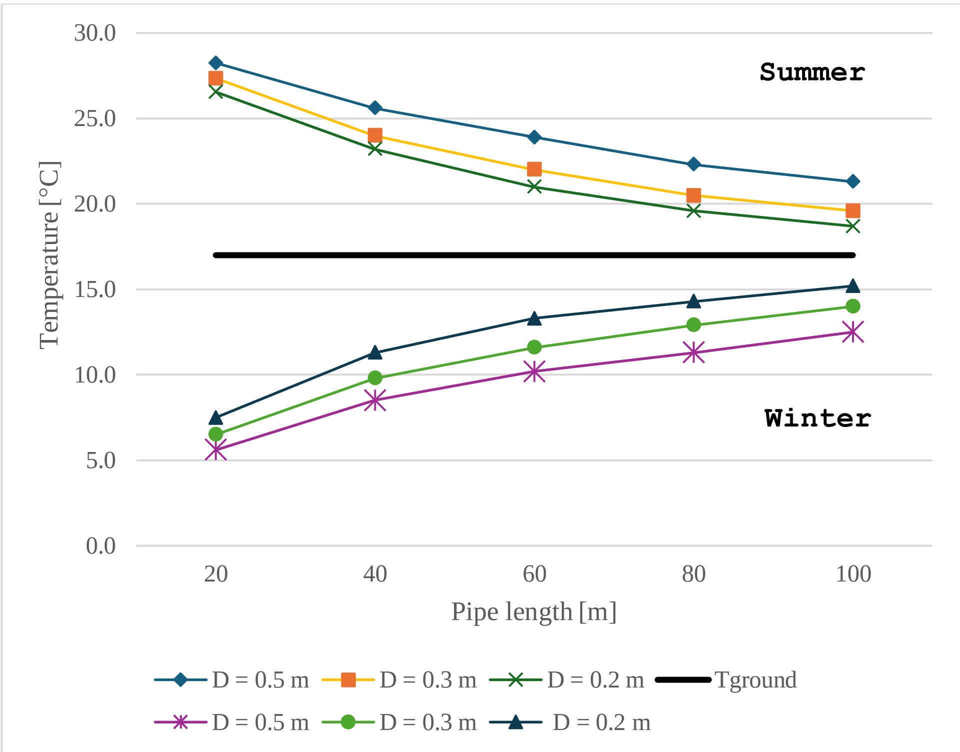


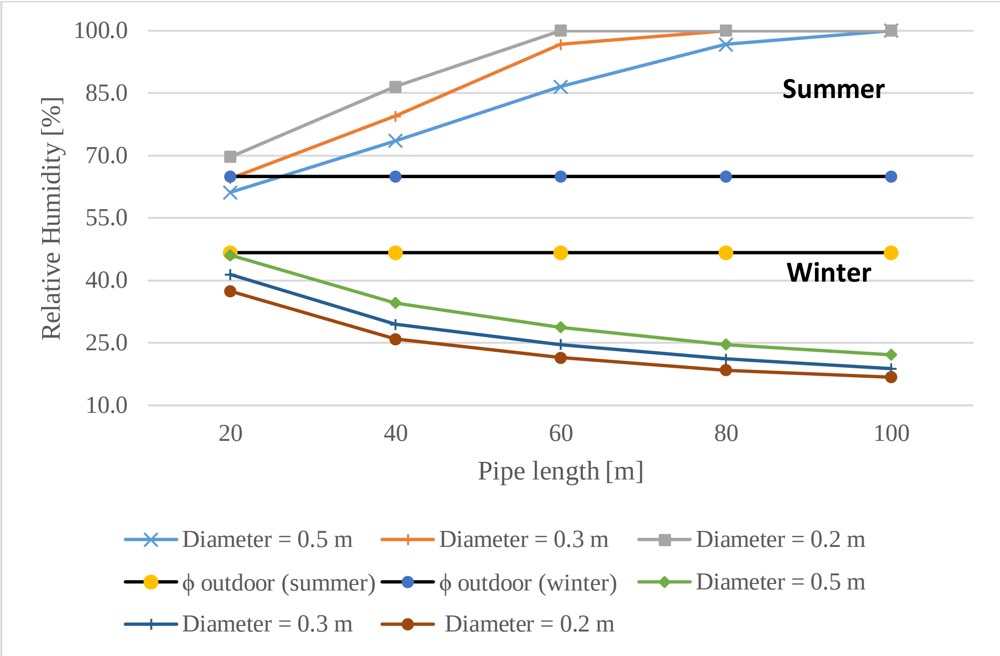
Figure 22. Temperature of the air at the exit of EAHE for different pipe lengths: (a) Budapest and (b) Naples.

As it can be seen in the Figure 22, employing the smallest tube diameter (D = 0.2 m, with an inlet air velocity of 2.38 m/s) combined with the longest pipe (100 m) results the most pronounced air temperature variation within the EAHE. In Budapest, under summer design conditions ($T_{outdoor}$ = 32°C), the air temperature at outlet of EAHE progressively shifts towards the stable soil temperature (T_{ground} = 12.3°C), confirming that the ground has strong thermal damping effect. This thermal damping effect is widely recognized in subsurface heat exchange systems and represents a key advantage of EAHE technology in reducing design thermal loads. In practical HVAC engineering applications, such attenuation can significantly decrease the required capacity of downstream mechanical cooling systems, particularly in climates with high daytime temperature variations. For D = 0.5 m, the outlet temperature decreased from 27.3 °C at 20 m to 18.1 °C at 100 m, corresponding to a temperature drop of 4.7–13.9 °C. For D = 0.3 m, a stronger attenuation is observed, ranging from 5.6 to 15.8 °C. The maximum cooling potential is attained with D= 0.2 m and L = 100 m, producing a temperature reduction of 17.1°C.

A similar EAHE behaviour is observed in Naples, under summer design conditions ($T_{outdoor}$ = 31.8 °C) where the ground temperature remains relatively constant at T_{ground} = 17 °C. For D = 0.5 m, the outlet temperature decreased from 28.3 °C at 20 m to 21.3 °C at 100 m (ΔT = 3.5–10.5 °C), while the smallest diameter configuration yields the best temperature reduction equal to 13.1 °C. This results of thermal damping effect confirms the ability of the ground to act as a passive heat sink during peak cooling periods. From a system integration perspective, this behaviour supports the use of EAHE systems as a pre-conditioning stage in ventilation design, allowing engineers to downsize chillers or cooling coils and reduce operational energy consumption during peak summer conditions.

During winter operation, the EAHE system play the role of pre-heating device. In the continental climate of Budapest ($T_{outdoor}$ = −9.1 °C), heat transfers from the ground which is at a temperature of 12.3 °C to the ventilation air, increasing its temperature throughout the length of the pipe. As the pipe becomes longer, the outlet air progressively gets warmer, reflecting a stronger interaction with the subsurface thermal reservoir. This demonstrates the capability of EAHE systems to utilize the ground as a renewable thermal energy source. In practical applications, such passive pre-heating reduces reliance on conventional heating systems, which is particularly beneficial in cold climates where ventilation heating loads dominate building energy consumption. When D = 0.5 m, the exit temperature increases from −4.6 °C at 20 m to 5.5 °C at 100 m. For D = 0.2 m, the outlet temperature reaches 9.5 °C reflecting a heating gain of up to 18.6 °C compared to outdoor air. The same trends are detected in the Mediterranean climate of Naples ($T_{outdoor}$ = 2.3 °C), where the outlet temperature raise from 5.6 °C to 12.5 °C for D = 0.5 m, with the best heat gain obtained for the smallest diameter configuration.

(a)



(b)

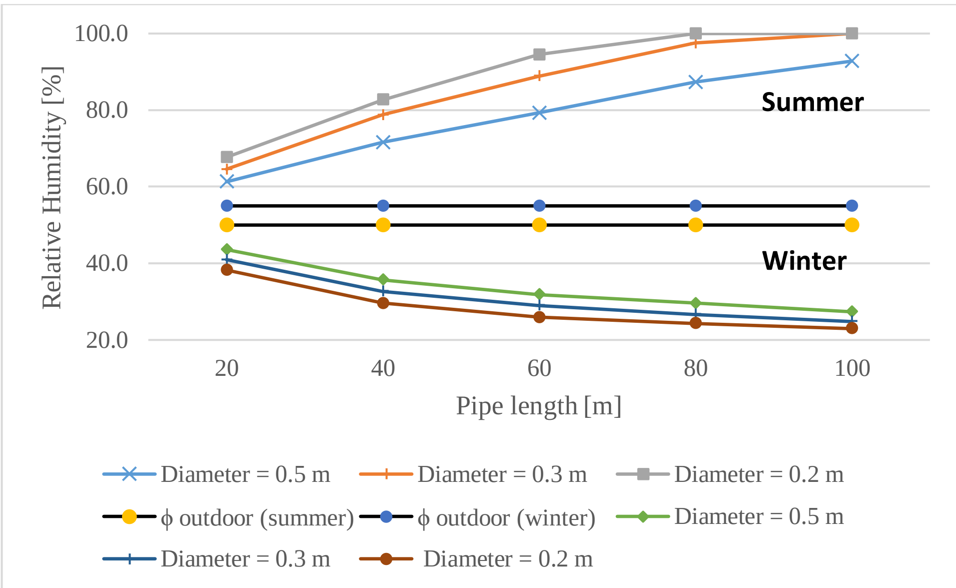


Figure 23. Relative humidity of the air at the exit of EAHE for different pipe lengths: (a) Budapest and (b) Naples.

In addition to the temperature reduction 'thermal effect', the EAHE produces strong hygrometric transformations (Figure 23). During summer operation, the reduction in air temperature causes an increment in relative humidity, towards saturation, with relative humidity rising from 46.7% at the EAHE inlet to 96.7% at the outlet (increment of 50%) in Budapest and from 50.0% at the EAHE inlet to 97.5% at the outlet (increment of 47.5%). This behaviour indicates that the conditions within the exchanger are favourable for moisture condensation. Contrariwise, throughout the winter operation, the humidity ratio stays relatively stable at both inlet and outlet of EAHE (1.23 g/kg in Budapest and 2.45 g/kg in Naples), whereas the relative humidity declines from 65% to 16.8% and from 55% to 23% in Budapest and Naples respectively. This markable reduction occurs due to sensible heating and the corresponding rise in saturation vapor pressure.

These findings are comparable trends with numerical and comprehensive measurements documented in the literature. Full-scale experiment by Wei et al. [222] has demonstrated that EAHE pre-conditioning can reduce the disparity between external and supplied air in both summer and winter conditions. The findings showed that a horizontal EAHE buried at 2.5 m depth was able to cool the average outdoor air by up to about 9.1°C compared to ambient conditions in a warm-humid climate, and to warm air by around 5.5°C. Moreover, the typical outdoor air relative humidity experiences an increase of 47% during cooling conditions and a decrease of 27.4% during heating conditions. This resembles the principles underlying thermal damping this research found. Comparable thermal attenuation was noted by Molina-Rodea et al. [105], who recorded air temperature reduction of 5-10°C in a shallow (less than 3 m) EAHE implemented in an office building. Additionally, the research finding about winter pre-heating trends is in line with previous research by Hu et al. [223], who found that the EAHE contribution increases as the temperature outside decreases in severe cold weather.

While the trends observed in this study align well with previous experimental and numerical investigations, the magnitude of temperature variation achieved, particularly for longer pipe lengths and smaller diameters suggests that system geometry plays a critical role in optimizing performance. This reinforces the importance of parametric design approaches in engineering practice, where pipe length, diameter, and burial depth must be carefully selected to match climatic conditions and building ventilation requirements.

The thermal efficiency Ɛ is defined as a representation of the EAHE system's capability to regulate soil temperature and its effectiveness in transferring heat between the surrounding soil and the air that flows through the buried EAHE pipe. This ratio can be expressed and quantified as follows:

$$\mathcal{E} = \frac{T_{in} - T_{EAHE-out}}{T_{in} - T_g} \quad (24)$$

Where T_{in} expresses the inlet air temperature (°C), which is the outdoor temperature, $T_{EAHE\text{-}out}$ is air temperature (°C) at the exit of the EAHE system and T_g represent ground temperature (°C).

The thermal efficiency of the EAHE in relation to pipe length and diameter for the two cities is illustrated in Figures 24 and 25. The findings for the two locations reveal that the thermal efficiency in both winter and summer is comparable, justifying the use of a single graph that applies to both cities. The maximum Ɛ recorded was 88% at a length of 100 m and a diameter of 0.2 m and it indicates that an EAHE with these dimensions demonstrate the capability to act as an effective passive air pre-conditioning system, reducing extreme outdoor air conditions prior to mechanical treatment by the air handling unit.

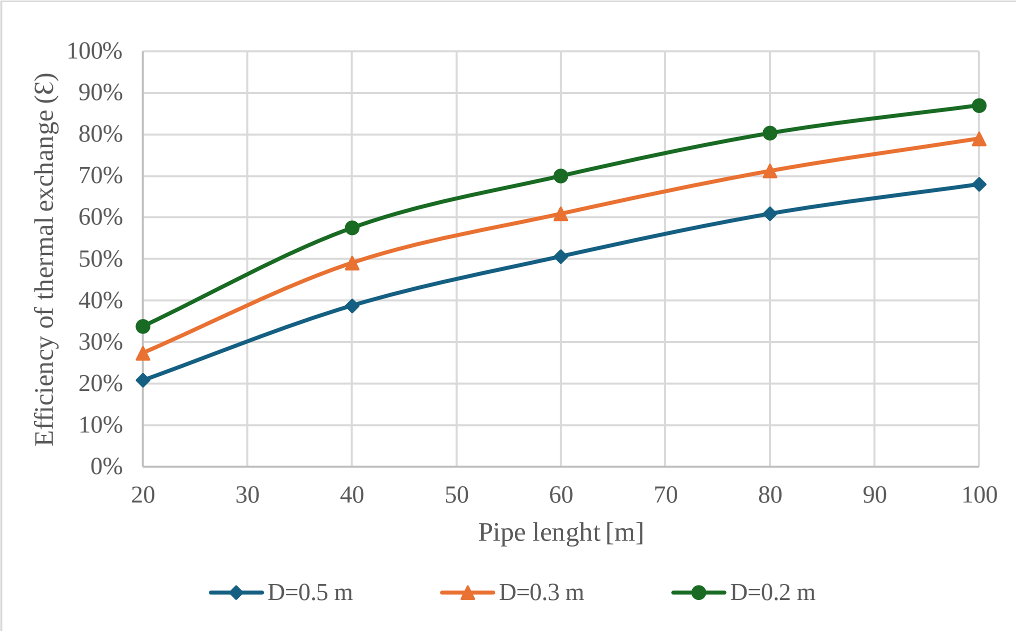


Figure 24. EAHE thermal efficiency as a function of pipe length and diameter for Budapest and Naples during winter season

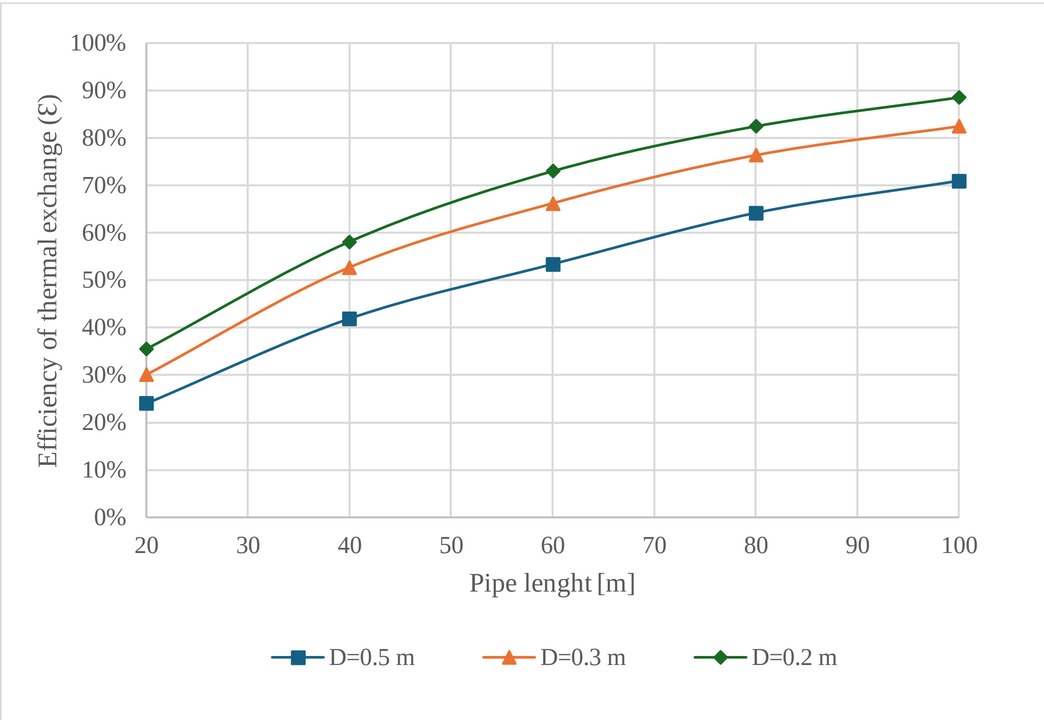


Figure 25. EAHE thermal efficiency as a function of pipe length and diameter for Budapest and Naples during summer season

4.4. Impact of Earth-Air Heat Exchanger on the Air Handling Unit

The impact of EAHE on the AHU is assessed by comparing two scenarios for the ventilation system configuration: a baseline AHU functioning with untreated outdoor air and AHU integrated with EAHE. In this section the focus is on quantifying the reduction in sensible and latent ventilation loads at the AHU inlet resulting from EAHE pre-conditioning device, by comparing the required heating and cooling coil capacities with and without the EAHE.

For the summer procedure, according to Eq. (17), the baseline cooling coil capacity of AHU is calculated using the design outdoor air temperatures 32°C for Budapest and 31.8°C for Naples. Without the integration of EAHE, the required cooling capacity of the AHU reached 123.7 kW in Budapest and 130.8 kW in Naples. When the EAHE is link upstream the AHU, instead of using outside air, the AHU processes pre-conditioned air at the EAHE output. As a result,cooling coil capacity is notably reduced to approximately 28.7 kW and 70.1 kW in Budapest and Naples respectively, highlighting the effectiveness of EAHE pre-conditioning in minimizing ventilation cooling requirements. This substantial reduction demonstrates that EAHE systems can directly contribute to design load cutting in HVAC systems. From an engineering standpoint, this enables the selection of smaller cooling equipment, reducing both capital investment and operational costs, while also improving system sustainability.

In the study during cooling operation of the hybrid system, Eq. (18) is used to calculate the re-heating coil capacity to restore supply air conditions to the designated indoor comfort setpoint. Since, this process is not affected by the pre-conditioned air, but rather by indoor thermal requirements, the re-heating demands present only slight influence from the implantation of EAHE and is therefore not emphasized in the results discussion (see Annex 2).

For the winter procedure, according to Eq. (19), the baseline heating coil capacity of AHU is calculated using the design outdoor air temperatures -9.1°C in Budapest and 2.3°C in Naples. In the absence of EAHE, the necessary heating capacity of the AHU determined to be 106.7 kW and 65.1 kW, respectively. When the EAHE is connected before the AHU, due to the ground exchange, the ventilation air enters the hybrid system at a higher temperature, leading to a significant decrease in heating coil capacity, measuring around 38.4 kW in Budapest and 17.7 kW in Naples. Such reductions are particularly relevant in ventilation-dominated buildings such as schools, where outdoor air requirements are high. The integration of EAHE systems can therefore play a crucial role in achieving energy-efficient ventilation design and compliance with modern building energy regulations.

Overall, positioning the EAHE upstream of the AHU results in a considerable decrease in both heating and cooling design capacities of the AHU coils during the winter and the summer as stated in Figures 26 and 27 for both climatic chosen locations.

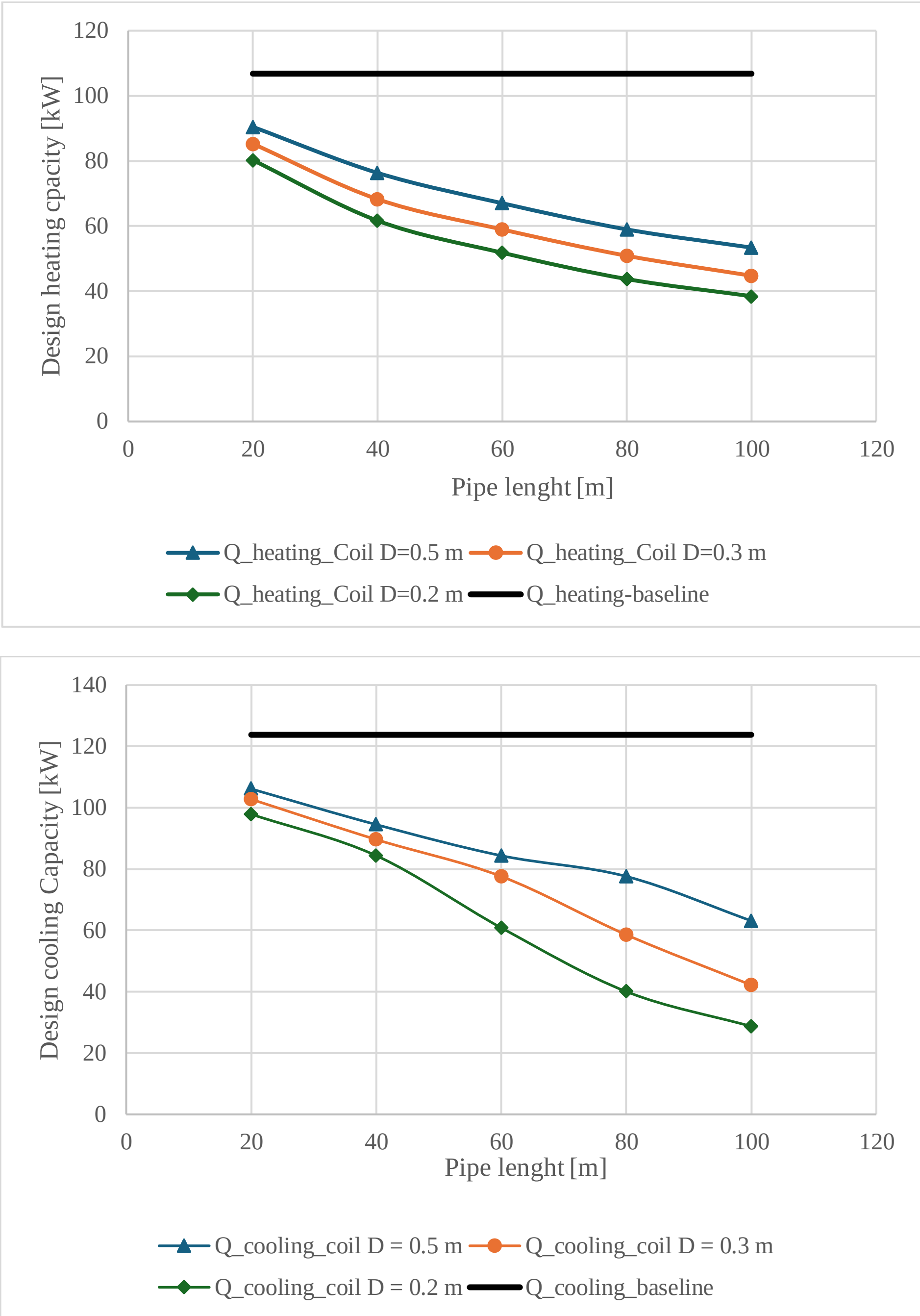


Figure 26. Design heating/cooling coil capacity variation when using EAHE in Budapest

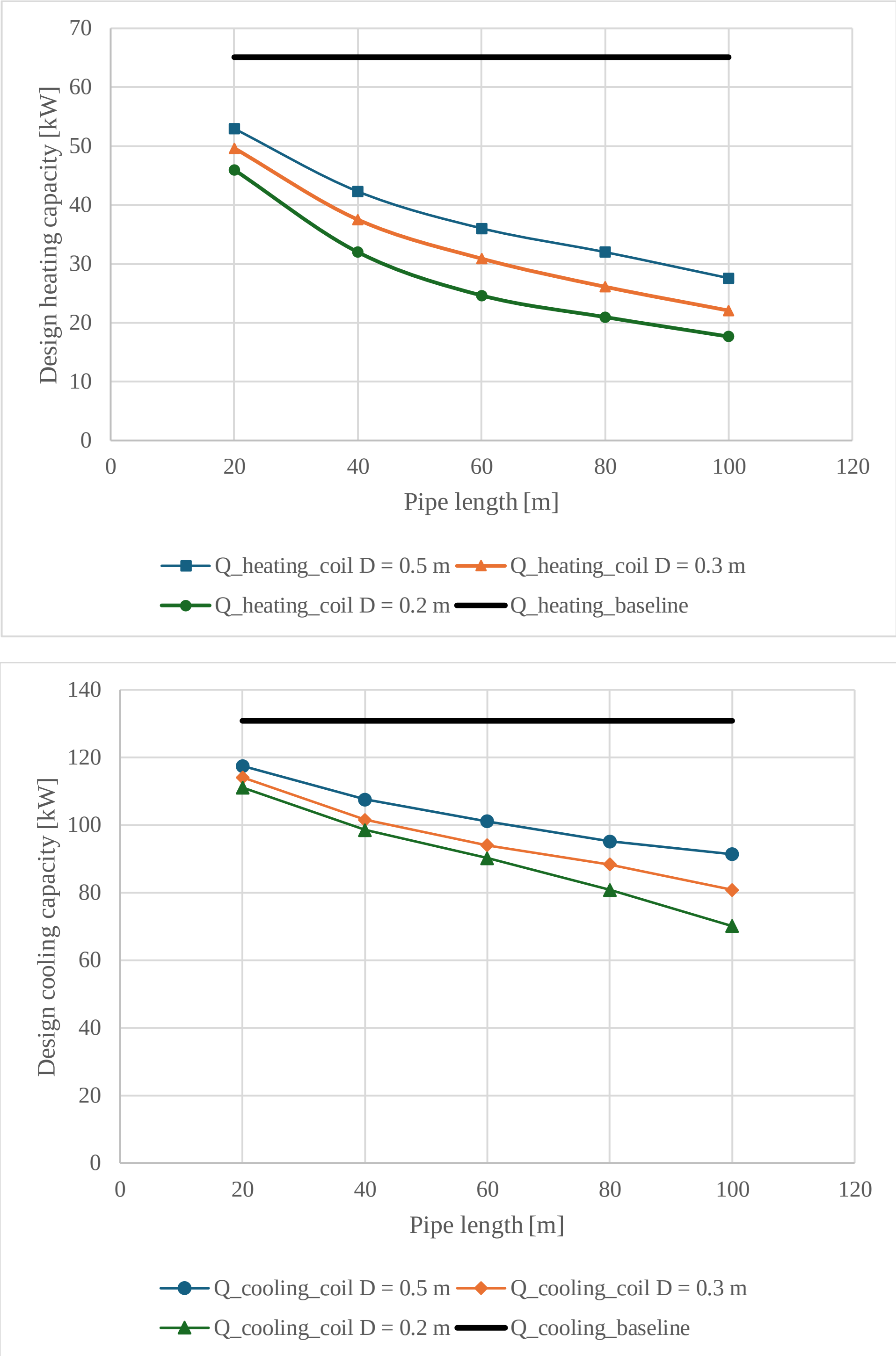


Figure 27. Design heating/cooling coil capacity variation when using EAHE in Naples

While a general monotonic drop in coil capacity is observed with increasing EAHE pipe length, notable deviations in the trend appear at certain pipe diameters and lengths. These deviations resemble to configurations where the air temperature inside the EAHE get closer to its dewpoint, attributed to the occurrence of water vapor condensation within the EAHE.

As condensation begins, it slightly changes the thermodynamic conditions of the air entering the AHU and is reflected as out-of-trend in the design cooling capacity curves. The associated mass flow rate of condensed water is calculated using Eq. (12) and is relatively quantified as a small amount, reaching a highest of 0.0122 kg/s in Budapest and 0.0045 kg/s in Naples for the configuration L = 100 m and D = 0.2 m. These values indicate that condensation varies the performance curve shapes; however, its quantitative impact on AHU load reduction is less important compared to the influence of the EAHE's sensible heat exchange. Similar interactions regarding condensation, near-saturation outlet conditions, and apparent changes in cooling-load trends have been documented in the literature. Recent CFD study [224] which consider variations in humidity and wall condensation indicate that as air approaches its dew point within the buried duct, latent phenomena can alter heat transfer dynamics, leading to non-linear performance variations across different lengths and diameters, particularly in smaller diameters and with high-RH inlet air. Moreover, experimental investigation conducted in China [188] under hot-humid climatic conditions confirm that EAHE for summer operation can partially dehumidify the ventilation air before it delivers to the mechanical system, leading to diminish the required dehumidification demand at the cooling coil. From a practical engineering perspective, the occurrence of condensation within the EAHE highlights the need for proper drainage design and material selection to prevent moisture accumulation and ensure long-term system durability. Additionally, this latent effect can be advantageous, as it contributes to partial dehumidification of the incoming air, reducing the load on mechanical cooling systems.

4.5. Reduction of AHU design power demand

In order to guarantee the school building’s indoor thermal comfort needs, the baseline AHU must compensate the low external air temperature during the winter design conditions. In January, the design outdoor air conditions of −9.1 °C with 65% relative humidity in Budapest, and 2.3 °C with 55% relative humidity in Naples, are raised by EAHE-AHU system to the supply air set-point temperature of 20 °C, accompanied by a humidity ratio of 6.38 g kg^{-1}. In these conditions, the baseline heating coil capacity of the AHU without EAHE is recorded at 106.7 kW for Budapest and 65 kW for Naples.

Upon integrating the EAHE into the existing configuration, the ventilation air delivers to the heating coil at a higher temperature due to the heat exchange with the soil. The resulting reduction in design heating coil capacity then are reported in Tables 16-18 (a and b) for various pipe lengths and diameters. In these Tables, letters E represent air properties after the EAHE, A for air properties after the heating coil, and the S denote the supply air conditions (post-humidification) while case (a) is for Budapest while case (b) is for Naples.

Table 16 (a). Design capacity of the heating coil using EAHE considering various EAHE pipe lengths with diameter of 0.5 m and air velocity of 0.38 m/s in winter for Budapest.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{heating\ coil}$ [kW]	Heating coil power reduction [%]
	E	-4.6	46.1	1.2	-1.6		
20 m	A	20.0	8.5	1.2	23.2	90.5	-15.3
	S	20.0	43.4	6.4	36.3		
	E	-0.8	34.6	1.2	2.3		
40 m	A	20.0	8.5	1.2	23.2	76.3	-28.5
	S	20.0	43.4	6.4	36.3		
	E	1.7	28.8	1.2	4.8		
60 m	A	20.0	8.5	1.2	23.2	67.0	-37.2
	S	20.0	43.4	6.4	36.3		

80 m	E	3.9	24.6	1.2	7.0	58.9	-44.8
	A	20.0	8.5	1.2	23.2		
	S	20.0	43.4	6.4	36.3		
100 m	E	5.5	22.1	1.2	8.6	53.4	-50.0
	A	20.0	8.5	1.2	23.2		
	S	20.0	43.4	6.4	36.3		

Table 16 (b). Design capacity of the heating coil using EAHE considering various EAHE pipe lengths with diameter of 0.5 m and air velocity of 0.38 m/s in winter for Naples.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{heating\ coil}$ [kW]	Heating coil power reduction [%]
20 m	E	5.6	43.6	2.4	11.8	53.0	-18.6
	A	20.0	16.9	2.4	26.3		
	S	20.0	43.4	6.4	36.3		
40 m	E	8.5	35.7	2.4	14.7	42.3	-35.0
	A	20.0	16.9	2.4	26.3		
	S	20.0	43.4	6.4	36.3		
60 m	E	10.2	31.9	2.4	16.4	36.0	-44.6
	A	20.0	16.9	2.4	26.3		
	S	20.0	43.4	6.4	36.3		
80 m	E	11.3	29.6	2.4	17.5	32.0	-50.8
	A	20.0	16.9	2.4	26.3		
	S	20.0	43.4	6.4	36.3		
100 m	E	12.5	27.4	2.4	18.7	27.6	-57.6
	A	20.0	16.9	2.4	26.3		
	S	20.0	43.4	6.4	36.3		

Table 17 (a). Design capacity of the heating coil using EAHE considering various EAHE pipe lengths with diameter of 0.3 m and air velocity of 1.06 m/s in winter for Budapest.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{heating\ coil}$ [kW]	Heating coil power reduction [%]
20 m	E	-3.2	41.5	1.2	-0.2	85.3	-20.1
	A	20.0	8.5	1.2	23.2		
	S	20.0	43.4	6.4	36.3		
40 m	E	1.4	27.1	1.2	5.7	68.2	-36.1
	A	20.0	8.5	1.2	23.2		
	S	20.0	43.4	6.4	36.3		
60 m	E	3.9	24.6	1.2	7.0	58.9	-44.8
	A	20.0	8.5	1.2	23.2		
	S	20.0	43.4	6.4	36.3		
80 m	E	6.1	21.1	1.2	9.3	50.9	-52.4
	A	20.0	8.5	1.2	23.2		
	S	20.0	43.4	6.4	36.3		
100 m	E	7.8	18.8	1.2	10.9	44.7	-58.1
	A	20.0	8.5	1.2	23.2		
	S	20.0	43.4	6.4	36.3		

Table 17 (b). Design capacity of the heating coil using EAHE considering various EAHE pipe lengths with diameter of 0.3 m and air velocity of 1.06 m/s in winter for Naples.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{heating\ coil}$ [kW]	Heating coil power reduction [%]
	E	6.5	41.0	2.4	12.7		
20 m	A	20.0	16.9	2.4	26.3	49.7	-23.7
	S	20.0	43.4	6.4	36.3		
	E	9.8	32.7	2.4	16.0		
40 m	A	20.0	16.9	2.4	26.3	37.5	-42.4
	S	20.0	43.4	6.4	36.3		
	E	11.6	29.0	2.4	17.8		
60 m	A	20.0	16.9	2.4	26.3	30.9	-52.5
	S	20.0	43.4	6.4	36.3		
	E	12.9	26.6	2.4	19.1		
80 m	A	20.0	16.9	2.4	26.3	26.1	-59.9
	S	20.0	43.4	6.4	36.3		
	E	14.0	24.8	2.4	20.3		
100 m	A	20.0	16.9	2.4	26.3	22.1	-66.1
	S	20.0	43.4	6.4	36.3		

Table 18 (a). Design capacity of the heating coil using EAHE considering various EAHE pipe lengths with diameter of 0.2 m and air velocity of 2.38 m/s in winter for Budapest.

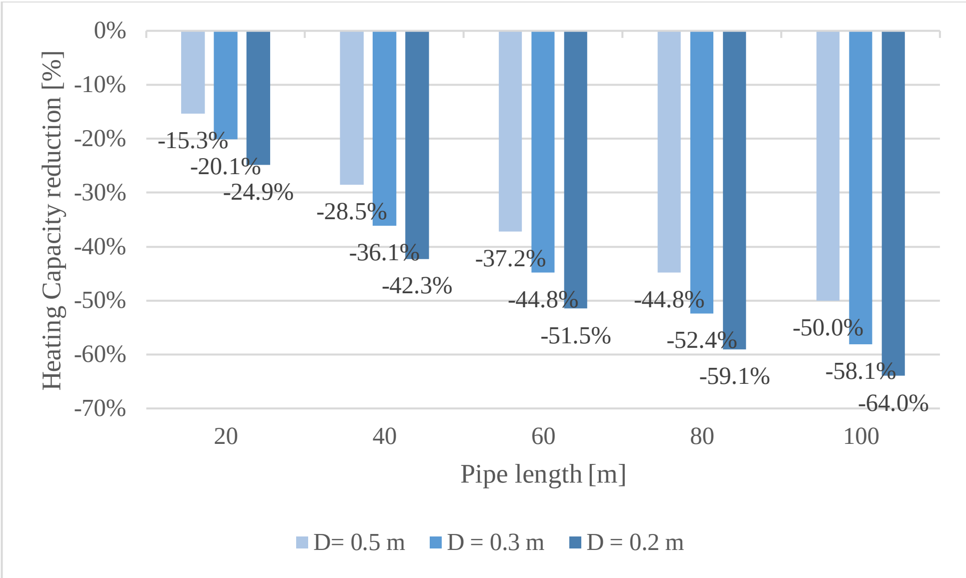
EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{heating\ coil}$ [kW]	Heating coil power reduction [%]
	E	-1.9	37.4	1.2	1.2		
20 m	A	20.0	8.5	1.2	23.2	80.2	-24.9
	S	20.0	43.4	6.4	36.3		
	E	3.2	23.7	1.2	6.3		
40 m	A	20.0	8.5	1.2	23.2	61.7	-42.3
	S	20.0	43.4	6.4	36.3		
	E	5.9	21.5	1.2	9.0		
60 m	A	20.0	8.5	1.2	23.2	51.8	-51.5
	S	20.0	43.4	6.4	36.3		
	E	8.1	18.5	1.2	11.2		
80 m	A	20.0	8.5	1.2	23.2	43.7	-59.1
	S	20.0	43.4	6.4	36.3		
	E	9.5	16.8	1.2	12.7		
100 m	A	20.0	8.5	1.2	23.2	38.4	-64.0
	S	20.0	43.4	6.4	36.3		

Table 18 (b). Design capacity of the heating coil using EAHE considering various EAHE pipe lengths with diameter of 0.2 m and air velocity of 2.38 m/s in winter for Naples.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{heating\ coil}$ [kW]	Heating coil power reduction [%]
	E	7.5	38.2	2.4	13.7		
20 m	A	20.0	16.9	2.4	26.3	46.0	-29.4
	S	20.0	43.4	6.4	36.3		
	E	11.3	29.6	2.4	17.5		
40 m	A	20.0	16.9	2.4	26.3	32.0	-50.8
	S	20.0	43.4	6.4	36.3		
	E	13.3	26.0	2.4	19.5		
60 m	A	20.0	16.9	2.4	26.3	24.6	-62.1
	S	20.0	43.4	6.4	36.3		
80 m	E	14.3	24.3	2.4	20.6	21.0	

	A	20.0	16.9	2.4	26.3		-67.8
	S	20.0	43.4	6.4	36.3		
	E	15.2	23.0	2.4	21.5		
100 m	A	20.0	16.9	2.4	26.3	17.7	-72.9
	S	20.0	43.4	6.4	36.3		

(a)



(b)

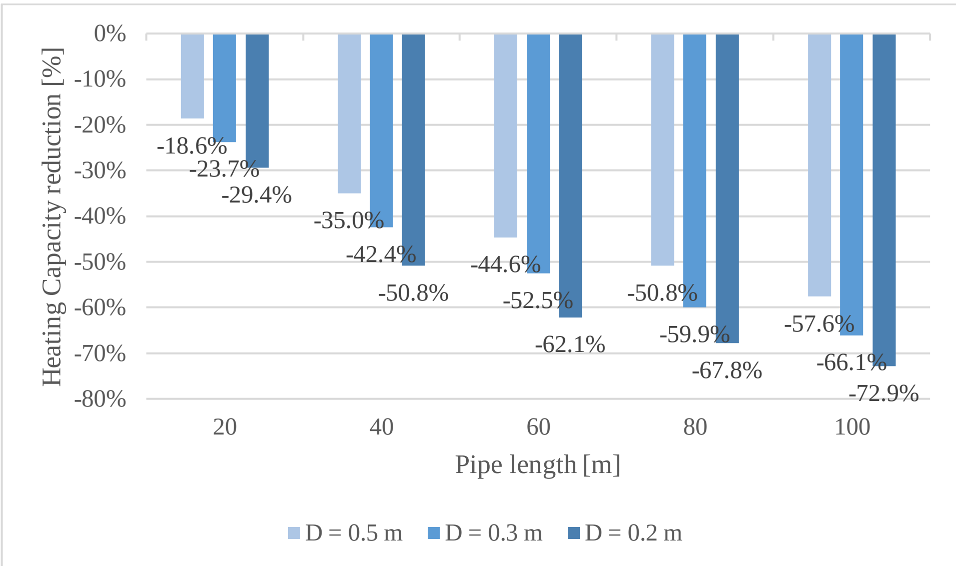


Figure 28. Reduction of heating coil design capacity through the implementation of EAHE in two distinct climatic conditions: (a) Budapest, (b) Naples.

The findings validate that the suggested hybrid EAHE–AHU system successfully lowers the heating power requirements of the ventilation system. For an EAHE with pipe diameter of 0.5 m and length of 20 m, the heating coil capacity is reduced by 15.3% in Budapest and 18.6% in Naples. Then the reduction becomes more valuable as the pipe length increases to 100 m, reaching 50% and 57.6% for Budapest and Naples respectively. This trend highlights the gradual improvement in thermal exchange as the residence time of the air within the buried pipes increases, allowing enhanced thermal transfer with the surrounding soil. Further, this trend reflects the direct relationship between residence time and heat exchange efficiency, which is a fundamental design consideration in heat exchanger engineering. Increasing pipe length enhances performance; however, it must be balanced against installation cost and available space constraints in real-world applications.

In fact, the most notable improvement in performance is observed with the smallest pipe diameter D = 0.2 m paired with the longest pipe length (100 m). With this configuration, the design capacity needed by the AHU heating coil is reduced to 38.4 kW in the case of Continental climate (Budapest) and to 17.7 kW in the case of Mediterranean climate (Naples), corresponding to reductions of 64% and 72.9% respectively, as a comparison to the baseline setup without EAHE. These results are illustrated in Figure 28 (a-b) highlighting the significant potential of the EAHE to serve as an efficient passive pre-heating solution, effectively lowering the design power demand of the AHU across both climatic contexts. In practical terms, such reductions translate into lower energy consumption, reduced greenhouse gas emissions, and improved system sustainability. These benefits are particularly important in the perspective of nearly zero-energy buildings (nZEB) and decarbonization strategies in the building sector.

With reference to summer design conditions, in July the baseline AHU cooling coil needs to counteract both sensible and latent loads linked to hot and humid outdoor air to reach the supply air set-point of 13 °C and a humidity ratio of 8.7 g kg^{-1}. In the absence of EAHE, the required design cooling coil capacity is 123.8 kW in Budapest and 130.8 kW in Naples. The summary of the reduction in cooling coil capacity, resulting from the integration of the EAHE upstream of the AHU, is presented in Tables 19–21 (a, b), which detail various pipe diameters and lengths.

Table 19 (a). Design capacity of the cooling coil using EAHE considering various EAHE pipe lengths with diameter of 0.5 m and air velocity of 0.38 m/s in winter for Budapest.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{cooling\ coil}$ [kW]	Cooling coil power reduction [%]
	E	27.3	61.2	13.9	63.0		
20 m	A	11.9	100	8.7	33.9	106.1	-14.3
	S	13.0	92.9	8.7	35.0		
	E	24.2	73.5	13.9	59.8		
40 m	A	11.9	100	8.7	33.9	94.5	-23.7
	S	13.0	92.9	8.7	35.0		
	E	21.5	86.6	13.9	57.0		
60 m	A	11.9	100	8.7	33.9	84.4	-31.8
	S	13.0	92.9	8.7	35.0		
	E	19.7	96.7	13.9	55.2		
80 m	A	11.9	100	8.7	33.9	77.6	-37.3
	S	13.0	92.9	8.7	35.0		
	E	18.1	100	13.0	51.2		
100 m	A	11.9	100	8.7	33.9	63.1	-49.0
	S	13.0	92.9	8.7	35.0		

Table 19 (b). Design capacity of the cooling coil using EAHE considering various EAHE pipe lengths with diameter of 0.5 m and air velocity of 0.38 m/s in winter for Naples.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{cooling\ coil}$ [kW]	Cooling coil power reduction [%]
20 m	E	28.3	61.3	14.8	66.1	117.5	-10.2
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
40 m	E	25.6	71.6	14.8	63.4	107.5	-17.8
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
60 m	E	23.9	79.3	14.8	61.6	101.1	-22.7
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
80 m	E	22.3	87.3	14.8	60.0	95.1	-27.3
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
100 m	E	21.3	92.8	14.8	58.9	91.3	-30.2
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		

Table 20 (a). Design capacity of the cooling coil using EAHE considering various EAHE pipe lengths with diameter of 0.3 m and air velocity of 1.06 m/s in winter for Budapest.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{cooling\ coil}$ [kW]	Cooling coil power reduction [%]
20 m	E	26.4	64.5	13.9	62.1	102.7	-17.0
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
40 m	E	22.9	79.5	13.9	58.5	89.6	-27.6
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
60 m	E	19.7	96.7	13.9	55.2	77.6	-37.3
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
80 m	E	17.7	100	12.7	49.9	58.6	-52.7
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
100 m	E	16.2	100	11.5	45.4	42.1	-65.9
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		

Table 20 (b). Design capacity of the cooling coil using EAHE considering various EAHE pipe lengths with diameter of 0.3 m and air velocity of 1.06 m/s in winter for Naples.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{cooling\ coil}$ [kW]	Cooling coil power reduction [%]
20 m	E	27.4	64.6	14.8	65.2	114.1	-12.8
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
40 m	E	24.0	78.8	14.8	61.7	101.5	-22.4
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
60 m	E	22.0	88.9	14.8	59.7	94.0	-28.2
	A	11.9	100	8.7	33.9		
	S	13.0	92.9	8.7	35.0		
80 m	E	20.5	97.5	14.8	58.1	88.3	

	A	11.9	100	8.7	33.9		-32.5
	S	13.0	92.9	8.7	35.0		
	E	19.6	100	14.3	56.0		
100 m	A	11.9	100	8.7	33.9	80.8	-38.2
	S	13.0	92.9	8.7	35.0		

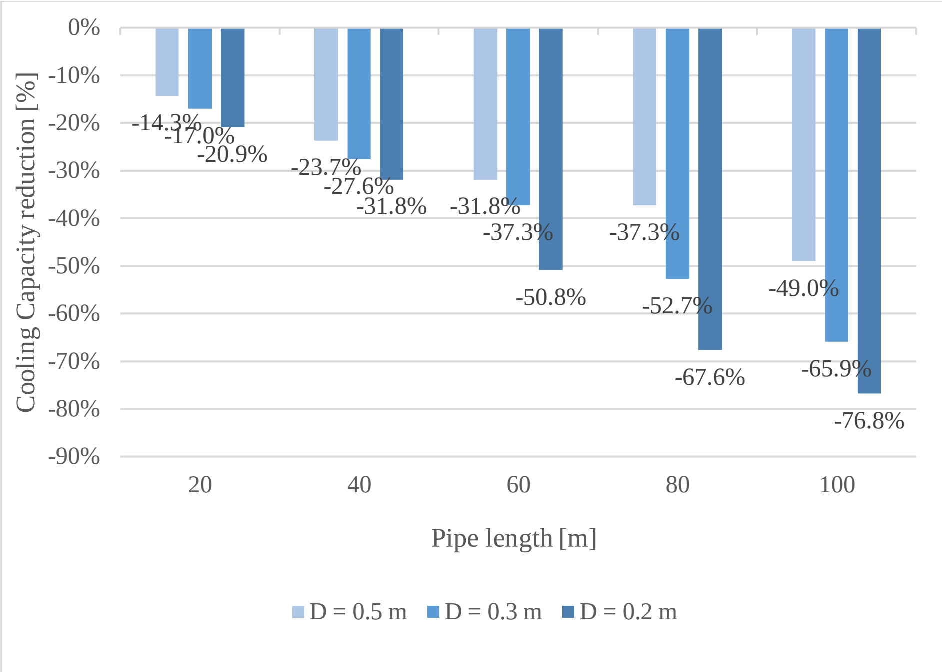
Table 21 (a). Design capacity of the cooling coil using EAHE considering various EAHE pipe lengths with diameter of 0.2 m and air velocity of 2.38 m/s in winter for Budapest.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{cooling\ coil}$ [kW]	Cooling coil power reduction [%]
	E	25.1	69.7	13.9	60.7		
20 m	A	11.9	100	8.7	33.9	97.9	-20.9
	S	13.0	92.9	8.7	35.0		
	E	21.5	86.6	13.9	57.0		
40 m	A	11.9	100	8.7	33.9	84.4	-31.8
	S	13.0	92.9	8.7	35.0		
	E	17.9	100	12.9	50.6		
60 m	A	11.9	100	8.7	33.9	60.8	-50.8
	S	13.0	92.9	8.7	35.0		
	E	16.0	100	11.4	44.8		
80 m	A	11.9	100	8.7	33.9	40.0	-67.6
	S	13.0	92.9	8.7	35.0		
	E	14.9	100	10.6	41.7		
100 m	A	11.9	100	8.7	33.9	28.7	-76.8
	S	13.0	92.9	8.7	35.0		

Table 21 (b). Design capacity of the cooling coil using EAHE considering various EAHE pipe lengths with diameter of 0.2 m and air velocity of 2.38 m/s in winter for Naples.

EAHE pipe length		T [°C]	Φ [%]	ω [g/kg]	h [kJ/kg]	$Q_{cooling\ coil}$ [kW]	Cooling coil power reduction [%]
	E	26.6	67.7	14.8	64.4		
20 m	A	11.9	100	8.7	33.9	111.1	-15.1
	S	13.0	92.9	8.7	35.0		
	E	23.2	82.7	14.8	60.9		
40 m	A	11.9	100	8.7	33.9	98.5	-24.7
	S	13.0	92.9	8.7	35.0		
	E	21.0	94.5	14.8	58.6		
60 m	A	11.9	100	8.7	33.9	90.2	-31.0
	S	13.0	92.9	8.7	35.0		
	E	19.6	100	14.3	56.0		
80 m	A	11.9	100	8.7	33.9	80.8	-38.2
	S	13.0	92.9	8.7	35.0		
	E	18.7	100	13.5	53.1		
100 m	A	11.9	100	8.7	33.9	70.1	-46.4
	S	13.0	92.9	8.7	35.0		

(a)



(b)

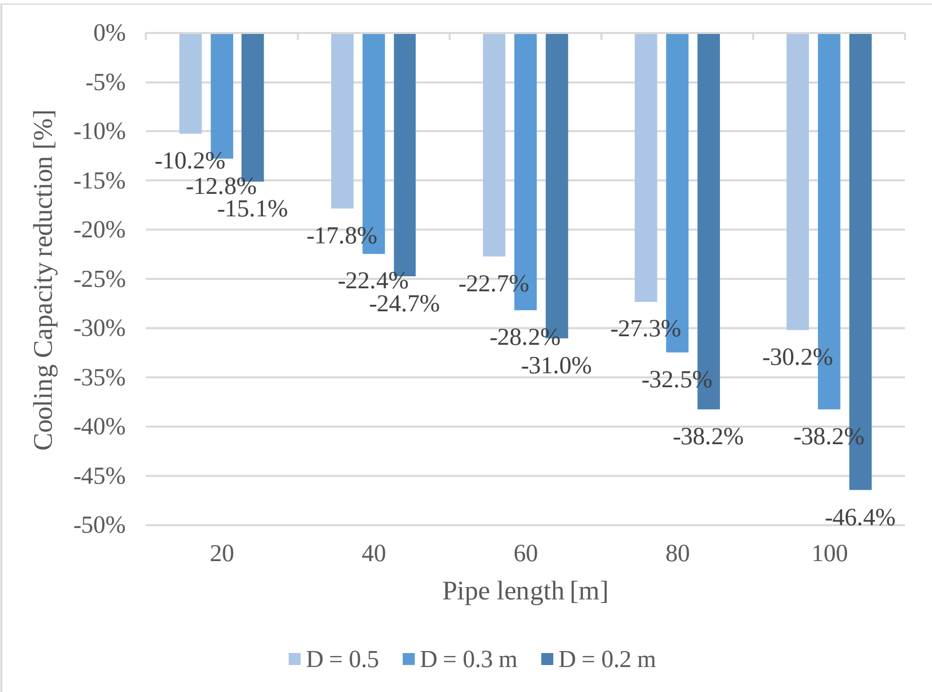


Figure 29. Reduction of cooling coil design capacity through the implementation of EAHE in two distinct climatic conditions: (a) Budapest, (b) Naples.

The influence of the EAHE on the cooling coil demand is minimal for shorter pipe lengths and larger diameters. In particular, for with pipe diameter of 0.5 m (v=0.38 m/s) and pipe length of 20 m, the reduction in design cooling coil capacity is relatively small, amounting to 14.3% in Budapest and 10.2% in Naples. This slight enhancement can be linked to inadequate air–soil contact duration and diminished convective heat transfer in the exchanger.

EAHE cooling performance face markable enhancement due to extending the resistance time of the air and increased convective heat transfer coefficient when the pipe diameter decreases and the length of it increases. In this regard, the most valuable capacity reduction is visualised at the smallest diameter (D = 0.2 m, v = 2.38 m/s) and the longest pipe length of 100 m configuration. With this setup, design cooling coil capacity decreases to 28.7 kW in Budapest and 70.1 kW in Naples. The observed values indicate significant decreases compared to the baseline scenario, with reductions of 76.8% for Budapest and 46.4% for Naples, as demonstrated in Figure 29 (a-b).

The significant relative reduction observed in Budapest can largely be attributed to the greater temperature gradient between the outdoor air and the undisturbed soil. The sensible cooling effect of the EAHE is enhanced as a result. Additionally, within a humid summer conditions, the EAHE partially lowers the latent load by reducing the ventilation air enthalpy and encouraging near-saturation effect inside the buried pipes. Consequently, the cooling requirements, both sensible and latent at the inlet of the AHU's coil are reduced, indicating the ability of the EAHE to function as passive pre-conditioning system across both climate types for summer ventilation. This behaviour suggests that EAHE technologies are especially effective in climate with significant temperature disparities between ambient air and ground temperature. Therefore, climate-specific design is essential, and engineers should evaluate local ground conditions and seasonal fluctuations when implementing EAHE systems.

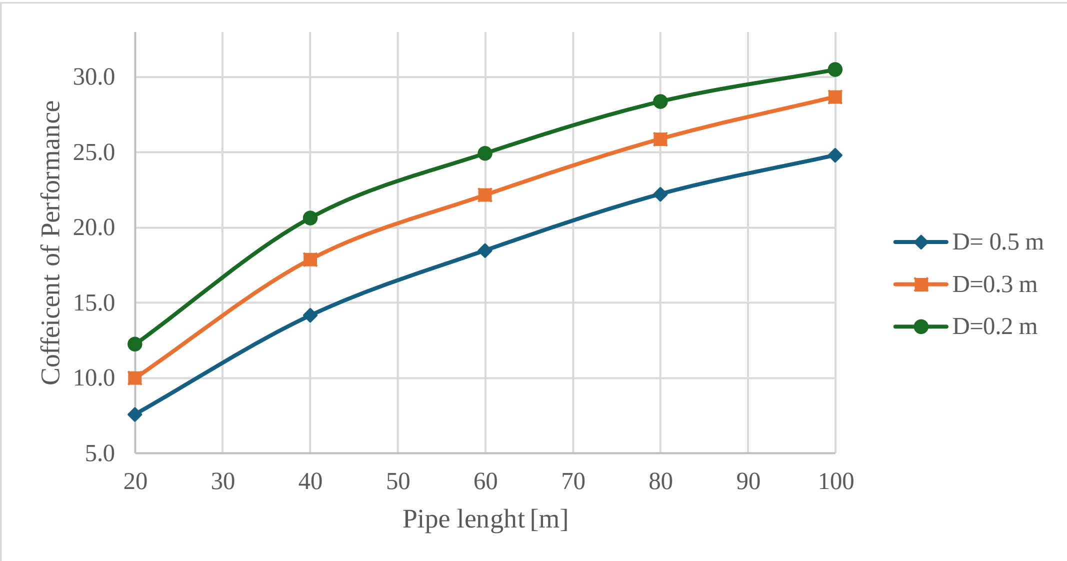


Figure 30 (a). COP of the hybrid EAHE–AHU system for different EAHE pipe lengths and diameters in Budapest for winter.

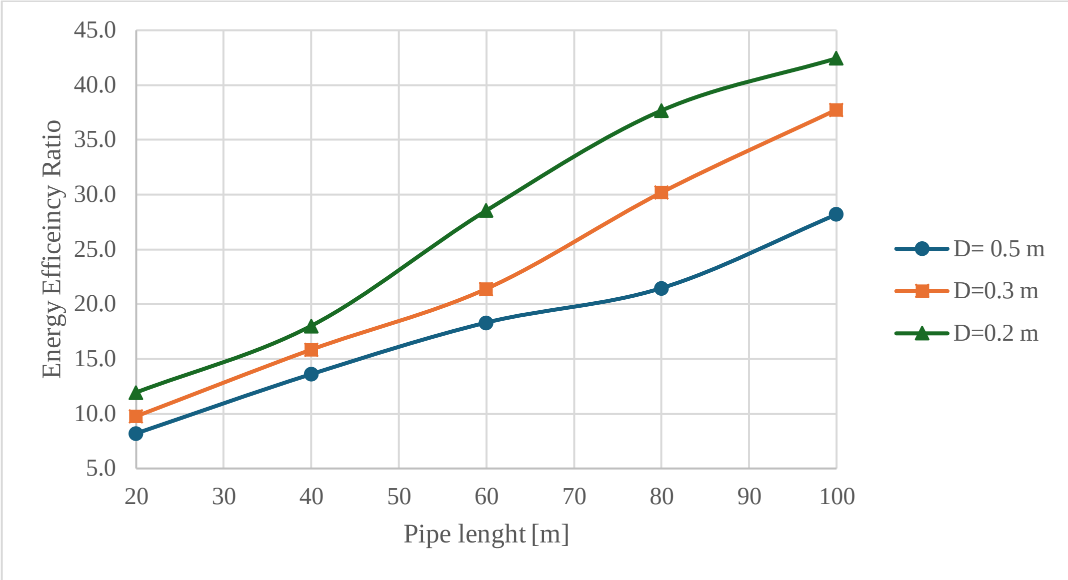


Figure 30 (b). EER of the hybrid EAHE–AHU system for different EAHE pipe lengths and diameters in Budapest for summer

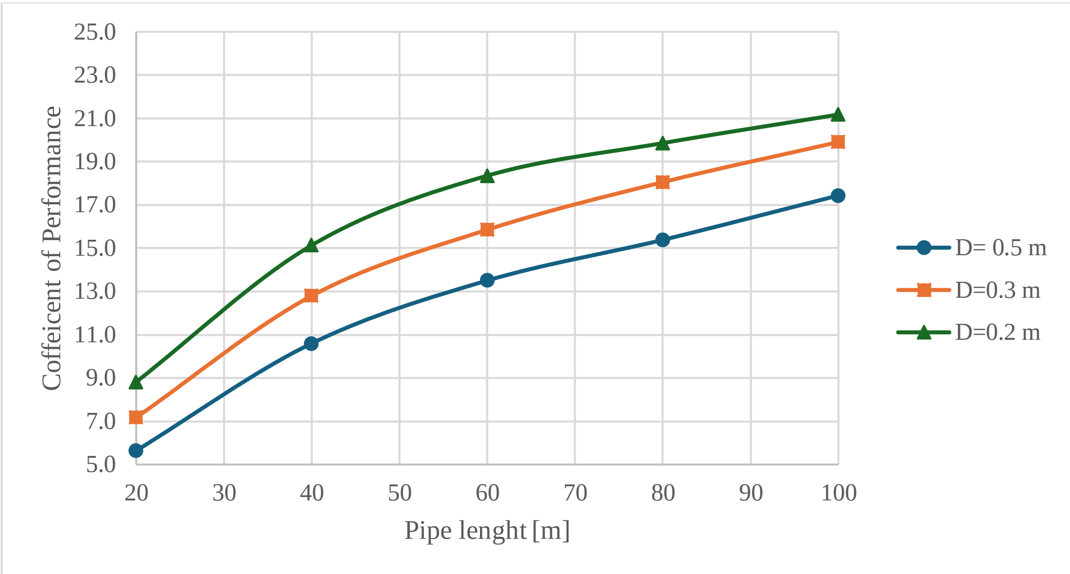


Figure 31 (a). COP of the hybrid EAHE–AHU system for different EAHE pipe lengths and diameters in Naples for winter

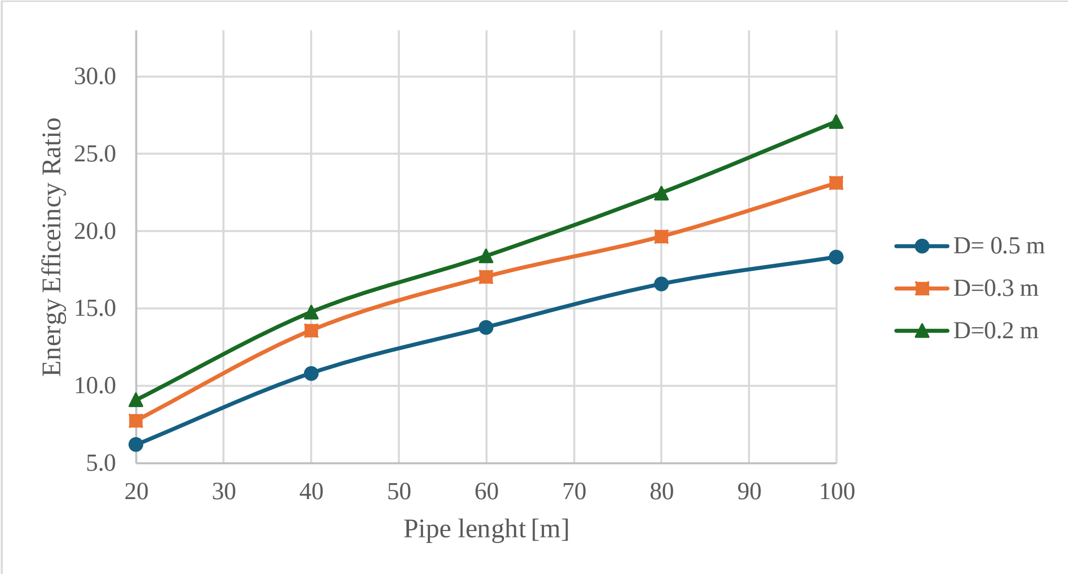


Figure 31 (b). EER of the hybrid EAHE–AHU system for different EAHE pipe lengths and diameters in Naples for summer

Figures 30 (a–b) and 31 (a–b) represent the winter coefficients of performance (COP) and summer energy efficiency ratio (EER) of the hybrid EAHE–AHU system for different pipe diameters and lengths in Budapest and Naples. With the fact that longer pipes with smaller diameter improve the heat exchange with the surrounding soil and increase residence time of the air inside the EAHE, the results of COP and EER in both sites rise with extending pipe length and shorting pipe diameters. The gain, however, tends to stabilize beyond about 80 m, indicating diminishing returns for additional excavation. Overall, the hybrid system performs better in the continental climate of Budapest than in Naples, because the higher temperature difference between outdoor air and deep soil improves the useful heat that can be extracted through the EAHE. The highest efficiencies are obtained in Budapest for a pipe length of 100 m and diameter of 0.2 m, with a COP of 30.5 and an EER of 42.4, confirming that the fan power demand remains small compared with the useful thermal energy delivered.

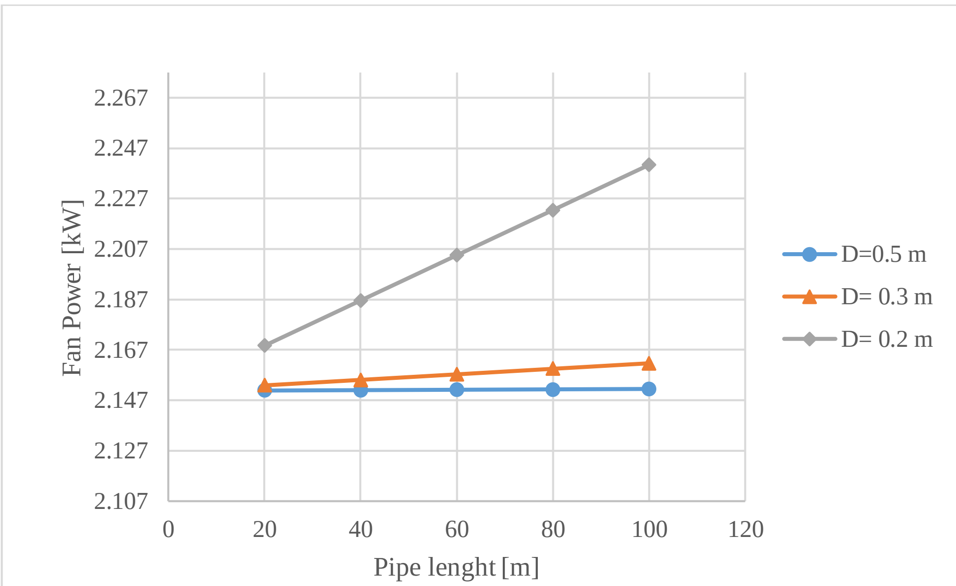


Figure 32. Variation of fan power when using different pipe diameters and lengths

The variation of the fan power after using various pipe length and diameter is illustrated in Figure 32. It is noted that this power is quite high with a diameter of 0.2 m. Although this configuration with smaller diameter enhances heat transfer, it concurrently raises frictional pressure losses along with the corresponding fan power requirements, explaining the increment in fan power observed in Fig.32. Therefore, the ideal design of an EAHE should not be assessed only through thermal efficiency; rather, it should adopt a multi-objective optimization strategy that balances heat exchange effectiveness with the energy demands of ventilation. Such optimization approaches are increasingly adopted in HVAC system design, where both thermal performance and auxiliary energy consumption (e.g., fan power) must be considered simultaneously. This guarantees that enhancements in heat exchange do not result in disproportionate increases in electrical energy consumption.

Overall based on the observed findings regarding reduction in AHU coil loads and the fan power increment, an EAHE configuration with an intermediate pipe diameter of 0.3 m and length of 80 m offer and balanced design solution. That is by obtaining significant thermal pre-conditioning while avoiding extreme costs in fan power (see Annex 4). This result is remarkably valuable for engineering practice, as it provides a realistic design recommendation that balances performance and energy efficiency. It suggests that extreme configurations (very small diameters or very long lengths) may not always be optimal when considering the overall system performance.

From a system-level perspective, the reductions in coil capacity observed in this study align with, and in certain instances exceed, those documented in earlier EAHE–HVAC integration research. D'Agostino et al. [214] analysed a comparable EAHE pre-treating unit integrated with an air-conditioning system across various global climates. Their findings indicated that, for a duct length of 100 m, the reductions in coil capacity varied between approximately 24% and 65%, depending on the climatic zone. Ben Ali et al. [225] investigated into the performance and the cost benefit of an EAHE integrated with an AHU, where they reported an important reduction in the mechanical cooling requirements. Under favourable design conditions, the researchers quantify the compressor power savings as 38.2%, resulting in annual operating cost savings of about 1470 $, with a reasonable 3.8-year payback period. Additionally, their economic analysis shows non-linear cost scaling, where installation expenses grow linearly with length ($370/m), while savings follow a diminishing returns pattern at a pipe length of 25m. The results then demonstrate that rectangular EAHE systems with 15-20 m range offers an optimal balance between performance (38.2–41.9% savings) and economic feasibility (3.8–4.6-year payback), proving it to be particularly suitable for commercial applications where energy efficiency and financial viability are essential factors. Despite the study documented system-level electrical savings, the direction and the magnitude kept align with the findings reported in this research, since reduction in the coil capacity directly refers to mechanical heating and cooling reduction.

Moreover, one-year experimental assessment confirms that during cooling operation of a fresh air-handling unit system, comprising an earth-air heat exchanger (EAHE) and a heat recovery unit, latent effects cannot be negligible in EAHE. Indicating that averagely, latent cooling representing about one-third of the total cooling capacity. These results support the condensation deviations observed in the present cooling loads trends [226]. Whitin this framework, the current analysis indicates that the configuration featuring a diameter of 0.2 m and a length of 100 m results in design heating coil capacity reductions of 64% in Budapest and 72.9% in Naples, alongside cooling coil capacity reductions of 76.8% and 46.4% respectively. The values observed are at the higher end, or just above, the range reported in the literature. This is justifiable as the present study emphasizes design-day peak loads in two climates with pronounced air–soil temperature variations, in contrast to the referenced studies that targeted various locations.

A comparable pattern is noted when these results are analysed alongside annual simulations and monitoring studies. Zhang et al. [227] conducted an evaluation of an EAHE-assisted ventilation system within the context of a hot-summer and cold-winter climate in China. Their findings indicated seasonal reductions of about 16% in cooling energy demand and 50% in heating demand for ventilation air. They observed maximum pre-cooling and pre-heating temperature differences of approximately 20–21 °C for a pipe length of 100 m. These values are consistent with the thermal efficiency up to 88% and the inlet–outlet temperature variations predicted in the current study for long and small-diameter pipes. On experimental scale, Hsu et al. [228] observed an EAHE system utilized by a restaurant in Taiwan under subtropical monsoon climate, achieving an annual COP of approximately 27.2 for a setup featuring multiple pipes 50 m length and 0.25 m diameter arranged in parallel. This is close to the COP of 30.5 and EER of 42.4 found in the present study for the Budapest case. The higher efficiencies noted in this study can be linked to the advantageous air–soil temperature gradient, as well as the evaluation of COP and EER at design operating conditions, excluding considerations for part-load operation or auxiliary plant energy consumption. Overall, the agreement with previous studies strengthens the validity of the present results, while the slightly higher performance observed under design-day conditions highlights the importance of considering peak-load scenarios in HVAC system sizing and design.

4.6. Summary of the chapter

In this chapter, the aim is to present and discuss the results of the numerical modelling of the integration of Earth Air Heat Exchanger upstream an Air Handling Unit for an existing educational building under continental (Budapest) and Mediterranean (Naples) climatic conditions. The analyses focus on the thermal transformation of the ventilation air inside the EAHE system, the influence of such system on the heating and cooling coil load of the AHU and the results of the reduction in the AHU design power demand. First, in accordance with the climatic design data and ventilation standards, the computed input parameters were established. By using the Kusuda–Achenbach equation, the temperature of the soil at depth of 2.5 m were estimated. Additionally, according to the ventilation requirements of the building, total air flow rate, mass flow rate and air velocities within the EAHE pipe were systematically calculated.

The findings demonstrate that EAHE is able to condition the outdoor air temperature by exploiting the thermal inertia of the ground. In winter, the EAHE acted as passive pre-heating technic by increasing the temperature of the ventilation air before it entered the AHU. In summer, such technology functioned as passive cooling device, significantly reducing the inlet air temperature and enthalpy and partially mitigating the latent load within humid conditions.

In both seasons, due to increased contact time of soil-air and convective heat exchange, EAHE configuration with the longest pipe and smallest diameter improved the effectiveness of heat exchange. These findings emphasize the dual role of EAHE systems in both sensible and latent load reduction, which is a key advantage over conventional ventilation strategies.

A substantial reduction in design heating and cooling coil capacities achieved through the integration of the EAHE upstream an AHU. While in cooling performance minor deviations were observed due to condensation inside the EAHE pipes, the overall reduction in AHU loads did not compromise by these effects. This confirms the robustness of the EAHE performance across diverse psychrometric conditions, affirming its applicability in real world HVAC systems.

Overall, across different climatic contexts, the EAHE integration results confirm its capability to decrease the design power demand of a mechanical ventilation system, ensuring indoor air quality and better comfort conditions. From an engineering application perspective , in school buildings, the outcomes highlight the EAHE as an applicable passive pre-conditioning technology for enhancing building energy performance, lowering operational costs and reducing HVAC system sizing.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This study proposes a fresh air technic comprising an earth-air heat exchanger (EAHE) and Air Handling Unit (AHU), to solve the problem of insufficient fresh air and save primary power use in severe cold or warm to hot regions. The investigation evaluated the thermal efficiency of an EAHE positioned upstream of an AHU within a school building situated in two different climatic environments: Naples (Southern Italy, Köppen climate classification: Csa) and Budapest (Hungary, Cfa). The findings indicate that the EAHE significantly improves the pre-conditioning of outdoor air by taking advantage of the relatively stable ground temperature, which remain higher than the outdoor air temperature in winter and lower in summer. During heating operation, the maximum temperature produced by EAHE was 9.5°C in Budapest and 15.2 °C in Naples and its maximum heating capacity was 68.3 kW and 47.4 kW while during summer was 14.9 °C and 18.7°C with a cooling capacity of 95.0 kW and 60.7 kW, respectively. Consequently, the hybrid EAHE–AHU configuration significantly reduces the heating and cooling capacity needed for the AHU coils in both climates.

The analysis confirms that the performance of the EAHE is strongly dependent on the geometric characteristics of the buried pipe. Reduced diameters enhance air velocity and optimize convective heat transfer, whereas longer pipes facilitate prolonged interaction with the surrounding soil. Among all configurations analysed, the combination of a 0.2 m diameter and a 100 m length demonstrated the highest thermal efficiency, reaching approximately 88%, and produced the most significant temperature variation between the inlet and outlet of EAHE. In winter, this configuration led to a decrease in design heating coil capacity by up to 64% in Budapest and 72.9% in Naples. Likewise, in the summer, the design cooling coil capacity experienced reductions of 76.8% and 46.4% in these two cities, respectively. The observed reductions validate the substantial role of EAHEs in lowering peak design requirements.

Further considerations are that, in accordance with Hungarian regulations, the operational timeframe for a heating system is set from 15 September until the end of May, limited to a duration of 10 hours per day. In contrast, Naples has its heating period from mid-November to March, also with a restriction of 10 hours per day. The results evident that while the decrease in design heating coil capacity is more pronounced in Naples (72.9%) than in Budapest (64%), the smaller reduction in a Continental climate is considered highly significant due to the long operational duration of the heating system, suggesting a subsequent increase in energy consumption. Further, considering the climatic characteristics, the operative period for the cooling system for Naples is established from early June to late July, lasting 6 hours each day. In contrast, for Budapest, the same period is designated for only 4 hours daily. The outcomes indicated that the impact of the cooling coil design capacity reduction is more significant in Budapest (76.8%); however, when taking into account the longer operational period of the system during the cooling season in Naples, the capacity reduction in the cooling coil (46.6%) becomes more critical.

A more detailed interpretation of the results uncovers several further considerations of wider significance. First, the EAHE functions not just as a passive heat exchanger; it actively regulates the thermal fluctuations of outdoor air by shifting it towards the relatively stable ground temperature. This stabilizing effect reduces the incidence of extreme thermal conditions at the

AHU inlet and may significantly influence the sizing of downstream HVAC components. Second, the system proves particularly benefits in climates categorised by serve winters or substantial seasonal fluctuations. As the temperature difference between air and soil is greater, the EAHE tends to operate more effectively during periods of peak demand. This indicates that the value of the EAHE integration extends beyond energy savings and includes enhanced operational resilience. The findings also highlight the presence of diminishing returns associated with pipe diameter reduction. Although smaller diameters enhance heat transfer, they concurrently elevate frictional losses and the corresponding fan power requirements. Therefore, the design of an optimal EAHE should not be assessed solely on thermal efficiency. Instead, it should adopt a multi-objective optimization approach balances heat exchange performance with the energy demands of ventilation.

5.2. Limitation of research

This study has certain limitations that should be acknowledged when interpreting the findings.

- ✓ The initial phase involves conducting the analysis based on steady-state design conditions, for representative winter and summer days. Consequently, the reported heating and cooling coil capacity reductions should not be interpreted as seasonal or annual energy savings.
- ✓ The EAHE is modelled as a singular horizontal buried pipe situated within homogeneous soil, neglecting the effects of groundwater, soil inhomogeneity, thermal interactions between the 40 parallel pipes present in the actual field, and potential long-term soil temperature variations caused by continuous operation.
- ✓ Further, the study emphasizes thermal performance; however, it does not specifically address issues like microbial growth, air filtration in the hybrid EAHE-AHU system, which could be essential for practical and real applications in school settings.

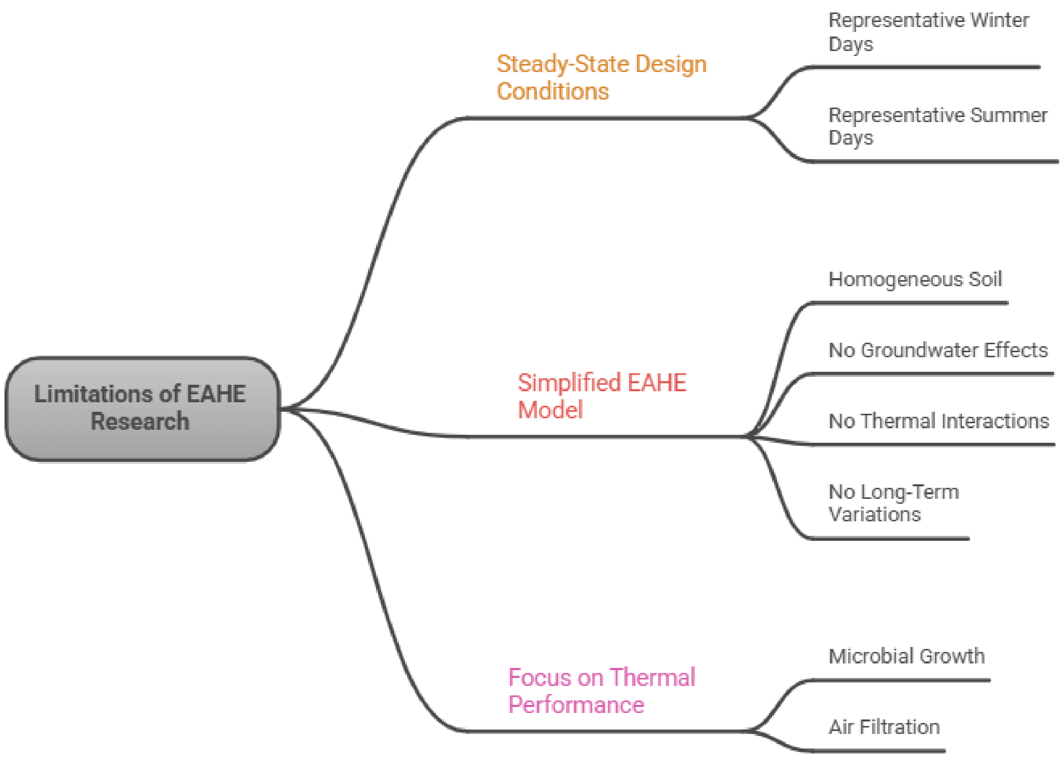


Figure 33. Limitations of the present study (source: author's idea designed by Napkin)

5.3. Recommendations and future development

- Complement coil-load reduction with annual performance:

Future investigations should concentrate on a more thorough assessment of the energy savings offered by the EAHE–AHU system. The savings extend beyond just the reduction of heating and cooling coil capacity; they are also influenced by the duration and frequency of the heating and cooling periods, which vary considerably between the two climatic contexts analysed (Budapest and Naples). A detailed analysis including seasonal operation, varying occupancy and soil thermal recovery could provide a more accurate estimation of the annual energy benefits of the hybrid system through annual dynamic simulations.

- Techno-economic analyses:

A specific analysis would be beneficial to assess technical-economic indicators, such as payback periods and net present value of the proposed configuration.

- Promote mechanical ventilation (AHU) adoption in Hungarian schools aligned with EU policy:

Although Air Handling Units as central mechanical ventilation systems are still not widely implemented within the existing school building stock in Hungary, where the predominant practice is remaining natural ventilation through window opening, promoting adoption of controlled mechanical ventilation systems is gaining high attention from recent European building and energy policy frameworks. EU-level directives and advice stress the importance of mechanical ventilation which is commonly used with heat recovery and high-efficiency control systems, in making sure that educational buildings have good indoor air quality while also fulfilling strict energy performance goals. In this context, the limited penetration of AHU-based systems in Hungarian schools represents not a technical constraint but rather an opportunity. As a forward-looking approach, the progressive introduction of advanced ventilation solutions, including hybrid configurations like EAHE-AHU systems, should therefore be encouraged in new buildings and deep renovations. Thus, this strategy aligns with European decarbonization, energy-efficiency, and indoor environmental quality objectives.

6. New scientific results

a) Contribution to knowledge: EAHE-AHU integration to school ventilation in the Budapest climate

In this research, a bibliographic coupling network of countries is done to better understand which of the locations are active in the investigation on Earth–Air Heat Exchangers integrated with Air Handling Units and the results are presented in Figure 11. Where the dominant contributor and central intellectual hub according to the analysis is Italy, showing a high bibliographic connection to China and limited interact to Portugal, and Hungary, meaning that these countries shared theoretical and methodological foundation. The findings of the literature review shows that the evaluation of an EAHE implemented upstream an AHU specifically for Budapest design day coil load reduction in a school building ventilation context remains barely reported in the open literature, as earlier studies related to Hungary and Central European climates, including comparative studies that feature Budapest focus on EAHE performance in different building typologies. Therefore, based on our research findings, there is a huge opportunity to conduct this research on hybrid system in Hungary.

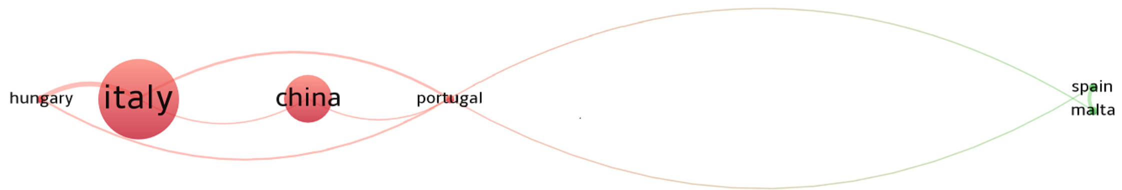


Figure 11. Network of bibliographic coupling among nations engaged in the study of EAHE combined with AHU.

Further, In the present study we combine several research keys words related to the topic of EAHE-AHU hybrid system including indoor air quality, air conditioning, EAHE, AHU, energy efficiency and shallow geothermal energy, highlighting the temporal evolution of the field based on average publication year it is illustrated in Figure 12. Based on this bibliometric analysis, there is a clear thematic shift in recent years (2020-2025) toward the integration of EAHE withing mechanical air conditioning systems. In general, the researchers focused on isolated heat transfer mechanisms, meanwhile in the last recent 5 years, a transition from the earlies studies aim toward applied research addressing whole system performance and environmental impact is suggested. We concluded this research shift by emerging keywords such as energy efficiency, air handling unit and capacity reduction. In contrast, older keywords related to fundamental cooling systems and numerical modelling appear predominantly in earlier periods, reflecting their role as the conceptual foundation of the field. Overall, the overlay visualization confirms that recent EAHE–AHU research is increasingly application-driven, performance-oriented, and aligned with low-carbon building objectives, underscoring the timeliness and relevance of further investigation in this area.

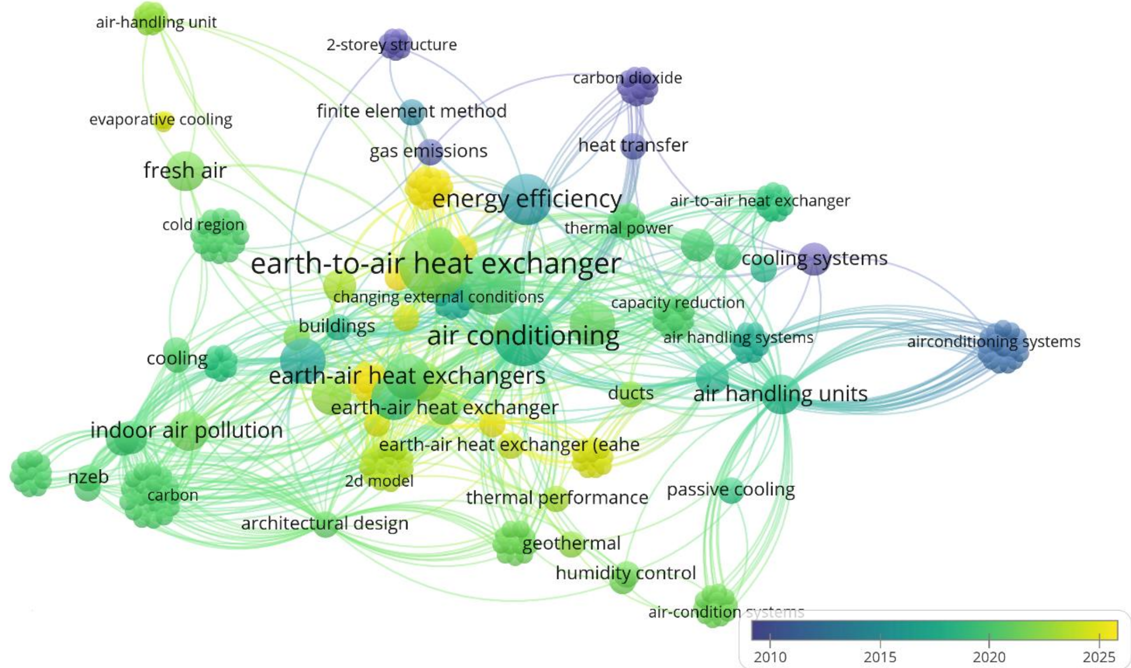


Figure 12. Visualization of keyword co-occurrence in EAHE–AHU research in the last recent 5 years (data retrieved from Scopus database on 27 December 2025)

b) Reduction of load at AHU level based on climate-dependent

The reduction in coil capacity of the existing AHU mechanical ventilation system that we calculated in this research are comparable to and in some cases exceed, those that were documented in earlier research on the integration of EAHE and HVAC systems. According to the literature, D'Agostino et al. [214] conducted an analysis of a similar EAHE pre-treating unit that was integrated with an air-conditioning system, examining its performance across different global climates. The results showed that, with a duct length of 100 m, the reductions in coil capacity ranged from about 24% to 65%, influenced by the climatic zone. Ben Ali et al. [225] examined the performance and cost benefits of an EAHE integrated with an AHU, noting a significant decrease in mechanical cooling needs. Under favourable design conditions, the analysis quantifies the compressor power savings as 38.2%, leading to annual operational cost reductions of about 1470 $, with a feasible 3.8-year payback period. A similar trend is observed when these findings are examined alongside with yearly simulations and monitoring studies. Zhang et al. [133] performed an assessment of an EAHE-assisted ventilation system in the framework of a hot-summer and cold-winter climate in China. The results demonstrated seasonal decreases of approximately 16% in cooling energy requirements and 50% in heating needs for ventilation air. Whitin this framework, the current analysis indicates that integrating an EAHE pre-conditioning before AHU yields a greater heating coil demand reduction (64%) in the continental climate of Budapest, while the reduction in cooling coil capacity is more significant in the Mediterranean climate of Naples (46.4%), reflecting the dominant heating or cooling characteristics of each climate. The results of our research are justifiable as the current research focus on design day peak loads in two selected climates, in contrast with the previous investigations.

c) Translation of EAHE performance into HAVC design metrics

This work assesses EAHE advantages through mechanical ventilation system loads. Among all the configurations analysed (D=0.5 m, D=0.3 m, D=0.2 m) and (L=20, 40, 60, 80, 100 m), the 0.2 m diameter and 100 m length pipe achieved the highest thermal efficiency (≈88%) and the greatest inlet–outlet air temperature difference equal to 18.6°C in winter and 17°C in summer for Budapest while, for Naples it is around 12.9 °C in winter 13°C in summer. Our research findings are consistent with Zhang et al. [133]. This improved thermal conditioning of the supply air through the integration of the EAHE translated directly into significant reductions in HVAC design loads. In winter, our optimal EAHE configuration reduced the design heating coil capacity by up to 64% in Budapest and 72.9% in Naples. In summer, the design cooling coil capacity was reduced by 76.8% in Budapest and 46.4% in Naples. These reductions confirm the effectiveness of EAHE, which directly support HVAC system size reduction and peak power demand evaluation.

d) Interpretation of psychrometric-based approach for EAHE summer performance

By analysing the fluctuations in humidity ratio and specific enthalpy, we confirm through the present study that latent load mitigation acts as key role in the hybrid system summer performance. Specifically, in the continental climate, the humidity ratio decreased from 14g/kg at the EAHE inlet to 11 g/kg at the outlet, corresponding to a latent moisture removal of $\Delta\omega = 3$ g/kh. This dehumidification process resulted in a latent enthalpy reduction of approximately 7.5 kJ/kg (the calculations in our research are done using latent heat of vaporization equal to 2501 kJ/kg). While in the Mediterranean climate, the humidity ratio decreased from 14.8 g/kg at the EAHE inlet to 13 g/kg at the outlet, corresponding to reduction in latent enthalpy of 2.5 kJ/kg. According to the calculations related to the air properties at the inlet and outlet of EAHE (provided in Annex 2 for Budapest case) and (provided in Annex 3 for Naples case), the sensible cooling reflected as temperature reduction remains the dominant component; however, the latent contribution represents around one-third (almost 29%) of the EAHE summer cooling effect which is associated with moister removal in the case of Budapest and around 15% in the case of Naples.

e) Cross-climate comparison with consistency:

In our research we modelled an identical school building geometry (total floor area of 1534 m^2) and envelope thermal performance (floor U=0.27 W/m^2K, windows U=1.70 W/m^2K, roof U=0.26 W/m^2K and wall U=0.19 W/m^2K) with a fixed ventilation demand of 10692 m^3/h calculated based on EN 16798-1 standard, identical EAHE-AHU system configuration and occupancy schedules from 8:30 a.m. to 2:30 p.m. for 347 person under two different European climates (Budapest and Naples) on a design day condition. Our aim is aligned with the European Union's decarbonisation goals by conducting a robust and transferable framework for assessing and comparing the effectiveness of the proposed hybrid ventilation technology across different climatic regions according to Koppen classification (Budapest: Cfa and Naples: Csa). The research primarily focusses on providing the adequate thermal indoor comfort condition which is established according to EN16798-1:2019 in schools (classroom) to be within the range of 20-24°C in winter and 23-26°C in summer both at equal relative humidity of 50% and ensuring indoor air quality while minimizing the energy consumption. Thereby in the adopted approach we maintain all the parameters related to the building and they EAHE-AHU system constant and varying only climate dependent inputs such as outdoor air temperatures (-9.1°C and 32°C in Budapest) (2.3°C and 31.8°C in Naples) based on 99% occurrence of ASHRAE handbook and ground temperature (12.3°C in Budapest and 17°C in Naples) according to Kusuda-Achenbach equation.

f) The need for multi-objective optimization in EAHE design:

It has been widely documented in the literature related to EAHE system, that longer pipes and smaller diameters enhance the effective heat-transfer surface and extend the residence time of the airflow, which in turn improves thermal performance. However, these design choices also result in increased frictional pressure losses. Consequently, the required fan power increases as the system is sized for greater heat exchange [149], [150]. This trend has been observed in our study as well. Under design day circumstances, according to the calculations we have done by decreasing the pipe diameter from 0.5 m to 0.2 m and increasing pipe length from 20 m to 100 m in the reason of improving soil-air heat transfer, the associated fan power of the hybrid system is simultaneously increasing from 2.15 kW to 2.24 kW (provided in Annex 4), which means more need for electrical energy (more initial cost). In parallel, the literature confirms that extending the pipe length or augmenting the number of pipes leads to elevated installation expenses, since material, excavation, and installation costs are typically calculated on a unit-cost-per-meter basis, resulting in a roughly linear increase in capital costs relative to the total pipe length. According to the economic analysis of Ben Ali et al. [225], the installation expenses grow linearly with pipe length ($370/m). Thus, in this context and in the absence our own economic analyses, we may conclude based on the existing studies that optimal EAHE design cannot be determined solely by thermal efficiency but should be based on a multi-objective optimization approach that balances heat exchange performance with ventilation energy requirements.

7. Theses of dissertation

1. **The integration of an Earth-to-Air Heat Exchanger (EAHE) with an Air Handling Unit (AHU) achieves peak-load performance comparable to international benchmarks under day boundary conditions:** the calculated reductions in heating and cooling coil capacities of the existing AHU system indicate that EAHE pre-conditioning can achieve performance comparable to, and in some cases better than, results reported in previous international studies. Earlier research has shown coil capacity reductions of 24–65%, compressor power savings of around 38%, and seasonal energy demand reductions of up to 50%. In comparison, the present design-day analysis

shows a 64% reduction in heating coil demand in the continental climate of Budapest and a 46.4% reduction in cooling coil capacity in the Mediterranean climate of Naples. These findings highlight that the performance of EAHE–AHU integration strongly depends on climatic conditions and becomes particularly significant under peak load scenarios. Therefore, this study provides new insight by focusing specifically on design-day peak performance, rather than on annual or seasonal evaluations as in most previous research.

2. **An optimized EAHE configuration (0.2 m diameter, 100 m length) achieves up to 88% thermal efficiency, enabling an important HVAC peak load reductions under design-day boundary conditions in continental and Mediterranean climates:** the parametric analysis of EAHE configurations demonstrates that a 0.2 m diameter and 100 m length pipe provides the highest thermal efficiency (≈88%) and the largest supply air temperature modification, reaching 18.6°C in winter and 17°C in summer in Budapest, and approximately 12.9–13°C in Naples. This enhanced pre-conditioning performance directly results in substantial reductions in HVAC design loads. The optimal configuration achieved heating coil capacity reductions of up to 64% in Budapest and 72.9% in Naples, while cooling coil capacity decreased by 76.8% in Budapest and 46.4% in Naples. These findings confirm that EAHE integration significantly contributes to HVAC system downsizing and peak load mitigation under design conditions.
3. **Thermodynamic analysis confirms that EAHE integration significantly mitigates latent loads under summer design-day boundary conditions in Central of Hungary and South of Italy:** the thermodynamic analysis of humidity ratio and specific enthalpy confirms that latent load mitigation plays a significant role in the summer performance of the hybrid EAHE–AHU system. In the continental climate of Budapest, the humidity ratio decreased from 14 g/kg to 11 g/kg ($\Delta\omega = 3$ g/kg), corresponding to a latent enthalpy reduction of approximately 7.5 kJ/kg, while in the Mediterranean climate of Naples the latent enthalpy reduction was 2.5 kJ/kg. Although sensible cooling remains the dominant component of the EAHE summer effect, the latent contribution accounts for nearly 29% of the total cooling impact in Budapest and approximately 15% in Naples. These findings demonstrate that moisture removal constitutes a substantial performance factor in continental climates and must be considered in hybrid system peak load evaluation.
4. **The study is transferable optimization framework that isolates climatic influence on hybrid EAHE–AHU systems by maintaining identical building geometry and ventilation demands while varying design-day boundary conditions for Budapest and Naples:** this research develops a robust and transferable comparative optimization framework for evaluating hybrid EAHE–AHU ventilation systems under different European climatic conditions by maintaining identical building geometry (1534 m^2), envelope thermal properties, ventilation demand (10692 m^3/h in accordance with EN 16798-1), system configuration, and occupancy schedules, while varying only climate-dependent boundary conditions. The analysis, conducted for design-day scenarios in Budapest (Cfa) and Naples (Csa), isolates the climatic influence by applying

standardized outdoor air temperatures (99% ASHRAE occurrence) and ground temperatures derived from the Kusuda–Achenbach equation. Within this framework, system performance is evaluated through the optimization of thermal comfort (20–24°C in winter, 23–26°C in summer, 50% RH), indoor air quality requirements in school classrooms while minimizing energy consumption, enabling a climate-sensitive assessment of optimal operating conditions in line with European Union decarbonisation objectives.

5. **Multi-objective parametric analysis reveals that optimal EAHE design requires balancing thermal efficiency against increased fan power and linear installation costs when varying pipe geometry under design-day load conditions:** the parametric analysis highlights the need for multi-objective optimization of EAHE design parameters, particularly pipe length and diameter. While increasing pipe length and reducing diameter improve thermal performance by enhancing heat-transfer surface area and airflow residence time, these changes simultaneously increase frictional losses, fan power demand, and installation costs. Under design-day conditions, reducing the pipe diameter from 0.5 m to 0.2 m and extending the length from 20 m to 100 m increased the required fan power from 2.15 kW to 2.24 kW, while installation costs scaled approximately linearly with pipe length (≈370 USD/m). These results demonstrate that optimal system design requires balancing competing objectives, including heat exchange effectiveness, ventilation energy demand, and economic investment, rather than maximizing thermal performance solely.

8. Published research articles

- Vityi Andrea; Diana D'Agostino; Nadjat Kouki; Federico Minelli; Francesco Minichiello. Reduction of the HVAC system size in school buildings through Earth-to-Air Heat Exchangers (EAHE). Case Studies in Thermal Engineering. Volume 81 (2026) 108025. **DOI:** 10.1016/j.csite.2026.108025. **Q1.**
- Kouki Nadjat; D'Agostino Diana; Vityi Andrea. Properties of Earth-to-Air Heat Exchangers (EAHE): Insights and Perspectives Based on System Performance. ENERGIES 18: 7 Paper: 1759, 16 p. (2025). **DOI:** 10.3390/en18071759. **Q1**
- Kouki Nadjat; Vityi Andrea; Belatrache, Djamel. Exploring Earth Air Heat Exchanger as an Innovative and Sustainable Application for Cooling and Heating. WASTE FORUM 2025: 3 pp. 205-223., 19 p. (2025). **Q4**
- Diana D'Agostino, Nadjat Kouki, Federico Minelli, Francesco Minichiello. Application of Earth-to-Air Heat Exchangers (EAHE) for Sustainable Energy Management in School Buildings. Journal of Physics: Conference Series 3143 (2025) 012050. ATI Annual Congress (ATI 2025), IOP Publishing. **DOI:**10.1088/1742-6596/3143/1/012050. **Q4**
- Kouki Nadjat; Vityi Andrea. The Use of Geothermal Energy for Sustainable Development and Economic Prosperity. Sopron, Magyarország : Soproni Egyetem Kiadó (2024) 821 p. pp. 365-379., 15 p. **DOI:** 10.35511/978-963-334-499-6.
- Saadi Zine; Kouki Nadjat; Boukhlef Djedjiga; Allali Malika; Amina Bekraoui; Abdelkrim Rouabhia. Experimental Analysis on Performance of a Solar Photovoltaic/Thermal (PV/T) Air Collector with a Single Pass. Advanced Computational Techniques for Renewable Energy Systems. Springer International

Publishing (2023) pp. 770-776. Paper: Chapter 78, 7 p. **DOI**: 10.1007/978-3-031-21216-1_78.

9. Summary

The building and industrial sectors presently account for around 39% and 31% [229] of total world energy consumption, respectively. In the building sector, roughly 40% of residential energy consumption, along with electrical usage, is attributed to HVAC systems [230], which also account for 36% of CO2 emissions [231]. Consequently, European policies highlight the necessity of reducing energy consumption in HVAC systems by 11.7% and CO2 emissions by a minimum of 55% relative to 1990 levels by 2030 [232], [233]. Today, it is broadly acknowledged that identifying solutions that simultaneously advance sustainability, energy efficiency, and adaptation to climate change is crucial. As an action, the "European Green Deal" [234] promotes the goal of attaining a climate-neutral Europe by 2050, focusing on the ambitious task of increasing the use of renewable energy across all sectors. Additionally, decarbonisation is vital, yet there is a pressing requirement to improve the operational energy efficiency of buildings [235]. This aspect is especially relevant for non-residential structures, such as school facilities, where guaranteeing satisfactory indoor air quality and thermal comfort must be balanced with the need to limit energy use. These buildings typically operate for long periods and require significant power, making efficiency improvements particularly impactful. The rise in buildings energy consumption has led to escalating concerns regarding their environmental impacts. Further, indoor air quality (IAQ) in school buildings is of extreme significance, as students generally spend approximately 6-8 hours each day within the school environment. This study investigates the integration of an Earth-to-Air Heat Exchanger (EAHE) into the HVAC system for an existing school building to fulfil the above-mentioned needs.

Earth-to-air heat exchanger (EAHE) technology is promising for space heating/cooling. However, in most climates, EAHE alone cannot provide significant indoor thermal comfort. Hybrid systems combining an EAHE and an air-handling unit (AHU) are highly recommended to use for indoor temperature regulation and energy conservation. The methodology of this research emphasizes evaluating the potential of an EAHE to enhance energy efficiency in school buildings across two distinct European climates: humid continental and Mediterranean, while maintaining identical building characteristics, ventilation requirements, and system configurations. This approach ensured that the observed differences in system performance were attributable solely to climatic influences. The study is based on two scenarios, aiming to evaluate the effectiveness of a standard HVAC system configuration in comparison to an innovative HVAC system design that incorporates an EAHE positioned upstream of the AHU. The thermal and hygrometric performance of the hybrid EAHE-AHU technology is evaluated in both summer and winter seasons. In the research, 2D mathematical model is adopted from the literature [214], [215] where multiple pipes lengths (20, 40, 60, 80 and 100 m) and diameters (0.5 m, 0.3 m and 0.2 m) are analysed. To ensure substantial energy savings, the air undergoes pre-treatment through an EAHE positioned upstream of the AHU, aimed at measuring the decrease in the design capacity of the heating and cooling coils of the AHU. The EAHE is important in pre-conditioning outdoor air, either cooling or heating it prior to its arrival at the AHU. The hybrid HVAC system operates in an open-loop configuration. The AHU provides the renewal of the indoor air by maintaining good air quality inside the building. Furthermore, the total ventilation airflow rate of the school building was estimated according to the Standard EN 16798-1. Variations in the air properties (temperature, humidity ratio, relative humidity and specific enthalpy) at EAHE outlet/inlet, design cooling/heating loads of the baseline AHU, the reduction in peak heating and cooling capacity of the AHU when the EAHE is integrated were examined. The outcomes show a maximum reduction of 17.1 °C in Budapest and 13.1 °C during summer and maximum gain of 18.6 °C in Budapest and 12.9 °C in Naples during winter for the EAHE outlet air temperature, demonstrating a clear capability of the EAHE to moderate the thermodynamic properties of outdoor air before entering the AHU.

From a system design perspective, the integration of the EAHE upstream of the AHU resulted in a measurable reduction in peak HVAC power demand during design days. This outcome has important implications for the sizing of AHU components, especially heating and cooling coils, which are typically designed to meet extreme outdoor conditions. The results showed that EAHE pre-conditioning led to a reliable reduction in AHU design coil loads across both climates. In winter design day, the reduction in design heating coil capacity was 38.4 kW in Budapest and 17.7 kW in Naples, equivalent to peak power reduction of 64.0 % and 72.9 % respectively. While under summer design day, this reduction was 28.7 kW in Budapest and 70.1 kW in Naples, representing 76.8 % and 46.4 % respectively.

Overall, this research further confirms that integrating EAHE systems with traditional mechanical ventilation units constitutes a practical hybrid HVAC approach for educational facilities, where ventilation requirements account for a substantial share of total energy consumption. The methodology adopted based on psychrometric analysis, mass and energy conservation, and design-day conditions, establishes a solid framework for assessing the contribution of EAHE at the system level, rather than as a standalone thermal component.

10. References

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ANNEXES

Annex 1: Data Input

Air mass flow rate	Power of Cooling Coil without EAHE Summer	Power of Heating Coil without EAHE winter	Tground	Total system air flow rate	Number of pipes	Single pipe air flow rate	Specific volume of air
m_a	Q_{AHU_Summer}	Q_{AHU_Winter}	T_g	V_{AHU}	N_{PIPES}	V_{PIPE}	V_i
[kg/s]	[KW]	[KW]	[°C]	[m^3/h]	[-]	[m^3/h]	[m^3/kg]
3.64	123.70	106.74	12.30	10692	40	269	0.82

Moist air constants		
PWS,0°C	Magnus-Tetens a	Magnus-Tetens b
[kPa]	[-]	[°C]
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3
0.61078	17.27	237.3

Annex 2: Calculation for Budapest_Winter

Annex 2: Calculation for Budapest_Summer

Annex 3: Calculation for Naples_Winter

Annex 3: Calculation for Naples_Summer

Annex 4: Fan Power, COP and EER calculations