Case Studies in Thermal Engineering

Advancing Sustainable Air Conditioning with CO2 Heat Pump and Earth-Air Heat Exchange Integration

--Manuscript Draft--

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Abstract:	The early development of refrigeration technology saw the use of natural refrigerants, but technical and safety challenges led to their replacement by synthetic alternatives. However, growing environmental concerns surrounding synthetic refrigerants have renewed interest in natural options, particularly carbon dioxide (CO_2). CO_2 has gained traction as a sustainable refrigerant, especially in commercial refrigeration, but its low critical temperature (30.98°C) limits efficiency in air conditioning applications. This limitation necessitates transcritical cycles, which are inherently less efficient.This study explores the integration of CO_2 with an Earth-Air Heat Exchanger (EAHE) to keep condensing temperatures below CO_2's critical point in direct expansion air conditioning systems, thereby improving efficiency. A mathematical model assessed the subsoil temperature profile in Sydney, Australia, revealing stable temperatures between 15.5°C and 20.1°C at a depth of 2.5 meters. Utilizing a 35-meter-long PVC pipe, the EAHE maintained an outlet temperature of approximately 19.5°C. This cooled air regulated the condensing temperature, enhancing system performance. The proposed CO_2-ACHP/EAHE system reduced energy consumption by 30% and total environmental weighted impact (TEWI) by 32% compared to R-410A while achieving a 59% reduction in both metrics relative to a CO_2 transcritical cycle. These findings highlight its potential as an energy-efficient, environmentally sustainable air conditioning solution.
Opposed Reviewers:	Rabindra Nath Mondal, Phd Australia, Jagananth University rnmondal71@yahoo.com Prof. Mondal is an expert in heat and mass transfer areas.
	Ming Nath Zhao, Phd Professor, Western Sydney University m.zhao@westernsydney.edu.au Prof. Zhao is an expert in heat and mass transfer and fluid mechanics research.
Response to Reviewers:	Dear Dr. Yan, Thank you for your email and for the opportunity to revise and resubmit our manuscript titled "Advancing Sustainable Air Conditioning with CO_2 Heat Pump and Earth-Air Heat Exchange Integration." We sincerely appreciate the valuable feedback provided by you and the reviewers. We have carefully addressed all comments and implemented the suggested revisions to improve the clarity, depth, and scientific rigor of the paper. A detailed point-by-point response outlining the changes made is included in the revised submission. We believe these revisions have strengthened the manuscript significantly, and we hope it will now meet the journal's publication standards.

	Thank you once again for your time and consideration. Kind regards, Fadi Alsouda, PhD (on behalf of all co-authors)

10 April 2025

Dear Editor,

I am pleased to submit our manuscript entitled *"A Novel Direct-Expansion Radiant Floor System Utilising Water (R-718) for Cooling and Heating"* for your consideration for publication in *Case Studies in Thermal Engineering*.

This study investigates the potential of using water (R-718) as a natural refrigerant in a direct expansion (DX) radiant floor system designed for both cooling and heating functions. The work presents a comprehensive thermodynamic analysis, system design framework, and performance comparison with conventional vapour-compression systems. Despite inherent challenges associated with water's thermophysical properties—such as high compression ratios and elevated discharge temperatures—the results demonstrate significant advantages in terms of environmental impact and energy efficiency. We believe this research offers valuable insights for the advancement of sustainable HVAC technologies and the broader application of ultra-low-GWP refrigerants in the built environment.

The manuscript has not been published, nor is it under review elsewhere. All authors have read and approved the manuscript and consent to its submission.

Thank you for considering our work. We look forward to the possibility of contributing to *Case Studies in Thermal Engineering*.

Kind regards,
Fadi Alsouda

Response to Reviewer #1

1. Clarify the novelty.
We appreciate the reviewer's comment. The introduction has been revised and highlighted to clearly define the novelty. To the best of our knowledge, this is the first study to integrate a *direct-expansion CO_2 air-conditioning and heat pump (ACHP)* system with an *Earth–Air Heat Exchanger (EAHE)* for condenser air pre-cooling under subcritical operation. Previous works primarily focused on CO_2 ground-source systems for heating, whereas this study evaluates the hybrid CO_2–ACHP/EAHE configuration for cooling applications through detailed *TEWI* and energy performance analyses.

2. Provide temperature-dependent thermophysical properties of CO_2.
Addressed in the *Methodology* section. The temperature-dependent thermophysical properties of CO_2 were incorporated into the simulation model and their sources and application are now clearly explained.

3. Explain soil moisture and seasonal variability.
Discussed in the *Results and Discussion* section. The impact of soil moisture and seasonal variation on long-term EAHE performance is now detailed.

4. Include a parametric study on EAHE pipe length and burial depth.
Addressed as shown in *Figure 4* (subsoil temperature variation at different depths) and *Figure 5* (EAHE outlet air temperature vs pipe length). Both figures demonstrate the influence of these parameters on system performance.

5. Provide validation for the EAHE subsoil temperature model.
Validation has been included in *Section 3.2*, comparing simulation results with published experimental data.

6. Add a mesh independence study and numerical uncertainty analysis.
Added and discussed in *Section 3.3*.

7. Discuss the impact of flow rate and air velocity on COP and TEWI.
Now analyzed and discussed in the *Results and Discussion* section. However, in this study the main focus is the EAHE thermal capacity and ability to remove the heat dissipated by the outdoor unit.

8. Analyze fan power consumption versus energy savings.
This analysis was added and highlighted in the *Results and Discussion* section.

9. Consider humidity and condensation in the EAHE air stream.
Addressed in the *Study Limitations* section (point 3), where the treatment of humidity and condensation effects is clarified.

10. Add energy and mass balance closure checks.
Energy and mass balance checks for the integrated system are presented at the end of the *Results and Discussion* section.

11. Include a monthly or seasonal performance breakdown.
Addressed in the *Sensitivity Analysis* section, showing COP variation by month.

12. Present streamline or velocity contour plots through the EAHE pipe.
Added as *Figures 9 and 10*.

13. Add a comparative performance table (R-410A, CO_2 transcritical, hybrid).
Included in *Table 3*, showing COP for the three cycle configurations.

14. Evaluate pressure drop and air-side resistance.
Analyzed and illustrated in *Figure 8.*

15. Discuss sensitivity to ground thermal diffusivity and pipe diameter.
Discussed in the *Sensitivity* section.

16. Provide economic or cost-benefit analysis.
Detailed cost data were unavailable; this has been acknowledged and included in the *Future Work* section.

17. Clarify frost formation or soil freezing consideration.
This study focuses on moderate climates where soil freezing is not applicable; the limitation is now clarified.

18. Improve figures and labeling.
All figures have been revised with labeled axes, color bars, and consistent units.

19. Ensure consistent units and symbols.
All units and symbols have been standardized throughout the manuscript.

20. Revise abstract with quantitative results.
The abstract has been revised to include numerical performance metrics and emphasize novelty.

21. Improve grammar and sentence structure.
The manuscript has been carefully edited for clarity, grammar, and readability.

22. Define all acronyms and variables on first use.
All acronyms and symbols are now clearly defined upon first mention.

23. Discuss scalability for larger capacities.
Addressed in the *Future Research Directions* section.

24. Discuss limitations of CO_2 in hot climates.
Added as point #2 in the *Future Research Directions.*

25. Add a section on future work (e.g., solar PV integration).
Included as point #4 in the *Future Research Directions.*

Response to Reviewer #2

We sincerely thank the reviewer for the positive and encouraging assessment of our work. We appreciate your recognition of the study's novelty and value in advancing sustainable air-conditioning technologies through the integration of CO_2 heat pump and Earth–Air Heat Exchanger (EAHE) systems. Your acknowledgment of the technical depth and clarity of the manuscript is greatly appreciated.

We have carefully addressed all the comments and recommendations provided, implementing substantial revisions to strengthen the technical analysis, improve clarity, and enhance the overall presentation. We believe that these revisions have significantly improved the quality and scientific rigor of the manuscript, and we are grateful for your constructive feedback that guided these improvements.

1. Acknowledge modeling-based nature and future experimental work.
Acknowledged and discussed in the last paragraph of the *Introduction*, highlighting plans for future experimental validation.

2. Clarify model assumptions (soil homogeneity, fan efficiency, steady-state).
A quantitative *sensitivity analysis* on COP and TEWI has been added in *Section 3.3* to evaluate these effects. All assumptions were added in the last paragraph of the *Methodology* section.

3. Clarify design parameter consistency among compared systems.
The first paragraph of the *Methodology* now states that identical design parameters (compressor type, heat exchanger capacity, and operating conditions) were applied for all system configurations to ensure fair comparison. All assumptions were added in the last paragraph of the *Methodology* section.

4. Justify refrigerant leakage assumptions.
This point has been addressed with reference to the *IPCC Guidelines (2006)*. A sensitivity analysis was performed considering leakage rates of 5%, 10%, and 15% to evaluate their impact on the Total Equivalent Warming Impact (TEWI). A 10% leakage rate was ultimately selected for the analysis, as it represents a mid-range and realistic value commonly reported across residential and commercial HVAC systems.

5. Strengthen novelty statement.
Expanded in the *Introduction*. This study uniquely evaluates a direct-expansion CO_2–EAHE integration for subcritical operation, supported by TEWI-based environmental comparison.

6. Improve figure numbering, labeling, and terminology.
All figures renumbered and relabeled. Consistent terminology "CO_2–ACHP/EAHE" is now used throughout.

7. Practical feasibility of 500 mm EAHE pipe.
Addressed in the *Results and Discussion* section, noting that equivalent airflow can be achieved through multiple smaller parallel pipes.

8. Update literature with recent references.
The *Literature Review* was revised to include multiple recent (2020–2025) studies relevant to CO_2-based hybrid and ground-coupled systems.

9. Enhance figure aesthetics.
New figures have been improved using color gradients and uniform formatting to enhance visual clarity.

Response to Reviewer #3

We sincerely thank the reviewer for taking the time to evaluate our manuscript and for acknowledging the interest and relevance of the presented results. We appreciate your constructive observation regarding areas that required further consideration. In response, we have carefully addressed all identified issues and implemented the necessary revisions to improve the accuracy, clarity, and depth of the analysis. We believe that the revised manuscript now provides a more comprehensive and robust presentation of the hybrid CO_2 heat pump and Earth–Air Heat Exchanger (EAHE) system, both in terms of technical rigor and practical relevance.

1. Add a comparison table with previous EAHE integrations.
Added and highlighted in the *Validation* section, comparing this study's findings with relevant literature.

2. Express novelty in the abstract.
Revised and highlighted; the abstract now clearly presents the research novelty and quantifies performance improvement.

3. Add a table comparing key findings with previous works.
Included in the *Validation* section as per the reviewer's request.

4. Include cost analysis.
Detailed cost data were unavailable; this has been acknowledged and deferred to *Future Work* recommendations.

5. Avoid personal pronouns.
All instances of "we," "our," and similar pronouns were replaced with formal phrasing.

6. Paraphrase "hybrid system shows promise for reducing."
Rephrased for clarity and academic tone.

7. English and grammar review.
The entire manuscript was carefully proofread for grammar, clarity, and readability.

Graphical Abstract

CO_2–EAHE Integrated Air Conditioning Heat Pump for Subcritical Operation

Earth–Air Heat Exchanger (EAHE)

- 35 m long PVC pipe
- 2.5 m burial depth
- Ambient air (~35°C) enters
- Soil at 15–20°C
- Outlet air ≈ 19.5°C

CO_2 Heat Pump Cycle

Compressor → Condenser (Gas Cooler)
→ Expansion Valve → Evaporator

Subcritical operation (T < 30.98°C)
Enabled by EAHE pre-cooling

Key Results

- COP ↑ 30% vs R-410A
- COP ↑ 59% vs CO_2 transcritical
- TEWI ↓ 32% vs R-410A
- TEWI ↓ 59% vs CO_2 transcritical

Maintaining subcritical operation through passive soil-air coupling enhances CO_2 cycle efficiency and reduces environmental impact.

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Author Contribution Statement

Fadi Alsouda: Conceptualization, Methodology, Modeling and Simulation, Data Analysis, Visualization, Original Draft Preparation, Writing final version.
Nick S. Bennett: Supervision, Methodology Review, Technical Validation, Review and Editing.
Mohammad S. Islam: Supervision, Project Administration, Conceptual Guidance, Review and Editing.

All authors have read and approved the final version of the manuscript.

Advancing Sustainable Air Conditioning with CO_2 Heat Pump and Earth-Air Heat Exchange Integration

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Highlights

- Stable subsoil temperatures facilitate efficient CO_2 cooling through EAHE integration.
- The hybrid system achieves a 30% reduction in energy consumption compared to R-410A.
- This study underscores the viability of CO_2 in air conditioning, broadening its scope of application.
- The system reduces total environmental impact by 32% relative to the conventional R-410A cycle.
- The hybrid system demonstrates 59% lower energy usage than standalone CO_2 transcritical cycles.

ABSTRACT

The early development of refrigeration technology relied on natural refrigerants such as carbon dioxide (CO_2), ammonia, and hydrocarbons. However, technical limitations and safety challenges led to their replacement by synthetic refrigerants. With increasing environmental concerns over high global warming potential (GWP) synthetic refrigerants, renewed attention has turned to natural alternatives, particularly CO_2, valued for its non-flammability, low toxicity, and negligible GWP. Despite these advantages, CO_2's low critical temperature (30.98°C) restricts its efficiency in air conditioning applications, as it often requires operation in transcritical cycles that are inherently less efficient.

This study introduces a novel integration of a CO_2 air conditioning heat pump (CO_2-ACHP) with an Earth-Air Heat Exchanger (EAHE) to overcome this limitation by maintaining the condensing temperature below CO_2's critical point, thus enabling more efficient subcritical operation. A mathematical model was developed to simulate the subsoil thermal behavior in Sydney, Australia, revealing stable ground temperatures between 15.5°C and 20.1°C at a depth of 2.5 meters. Using a 35-meter-long PVC pipe, the EAHE provided an outlet air temperature of approximately 19.5°C, effectively reducing the CO_2 condenser temperature and improving system performance.

The proposed CO_2-ACHP/EAHE system demonstrated a 30% improvement in coefficient of performance (COP) compared to conventional R-410A systems and achieved a 59% enhancement relative to a CO_2 transcritical system. Correspondingly, total equivalent warming impact (TEWI) decreased by 32% compared to R-410A and 59% compared to the transcritical CO_2 baseline. These results confirm the system's potential as an energy-efficient and environmentally sustainable alternative for air conditioning, introducing a novel pathway for enhancing CO_2 cycle efficiency through passive ground temperature regulation.

Keywords: Vapor Compression Cycle; Coefficient of Performance; Seasonal Energy Efficiency Ratio; Earth-Air Heat Exchanger; Total Environmental Weighted Impact.

Nomenclature:

α	thermal diffusivity (m²/s)	Re	Reynolds number
λ_{soil}	soil thermal conductivity (W/ m. K)	h	convective heat transfer coefficient (W/m^2 ·K)
ρ	soil density (kg/m³)	R_w	wall thermal resistance (m. K/W)
C_p	specific heat capacity (J/kg. K)	A_{in}	inner surface area (m^2)

$T_{(z,t)}$	subsoil temperature at depth/time (°C)	R_{soil}	soil thermal resistance (m. K/W)
T_m	annual mean temperature (°C)	R_{total}	total thermal resistance (m. K/W)
A_s	surface temperature amplitude (°C)	U	overall heat transfer coefficient (W/m^2 ·K)
$t_\circ$	phase constant (hours)	Ɛ	heat exchanger effectiveness
A	daily mean temperature amplitude (°C)	T_{Out}	outlet temperature (°C)
P_T	total pressure (Pa)	COP	coefficient of performance
P_V	dynamic pressure (Pa)	HP	heat pump
P_S	static pressure (Pa)	NTU	number of heat transfer units
V	air velocity (m/s)	ε	heat exchanger effectiveness
f	friction coefficient	P_T	total pressure (Pa)
D	pipe diameter (m)	P_V	dynamic pressure (Pa)
$\dot{V}$	volumetric flow rate (m³/s)	P_S	static pressure (Pa)
η	fan efficiency	TEWI	total environmental weighted impact (kg CO_2)
ΔP	pressure drop (Pa)	EER	energy efficiency ratio
Q	airflow in (m³/s)	SEER	seasonal energy efficiency ratio
h_{fg}	latent heat of vaporisation (kJ/kg)	ΔT_{fluid}	the temperature difference of the fluid (°C)
ΔT_{sup}	the refrigerant superheating (°C)	ΔT_{sub}	the refrigerant subcooling (°C)
W_{comp}	compressor work (W)	η_{mec}	mechanical efficiency

1. Introduction

Carbon dioxide has re-emerged as a promising natural refrigerant due to its non-flammability, chemical stability, abundance, and negligible global warming potential (GWP = 1). Its high vapor density allows for compact system designs, yet its low critical temperature (30.98 °C) imposes a major challenge in air conditioning applications. Under most conditions, CO_2 systems operate in a transcritical cycle, which leads to lower COP compared to subcritical systems using hydrofluorocarbons (HFCs) or hydrofluoroolefins (HFOs).

Early research focused on improving the transcritical CO_2 cycle through various system modifications. Sarkar (2012) found that CO_2's heat transfer coefficient was 20–100% higher than that of synthetic refrigerants in the saturated liquid state, potentially enabling smaller heat exchangers [1]. Sun et al. (2020) demonstrated that the COP of CO_2 cycles could be improved through partial cascading and subcooling techniques [2]. Llopis et al. (2016) and Kim et al. (2023) showed that introducing ejectors and intercoolers, respectively, could increase system performance by up to 16% and 12% [3,4].

Recent studies (2020–2025) have shifted toward hybrid and adaptive CO_2 systems to address climatic and operational limitations. Li et al. (2023) reported enhanced energy efficiency by integrating CO_2 systems with thermal energy storage, while Zhang et al. (2022) achieved significant COP gains through advanced two-stage compression with intercooling [5,6]. Sun et al. (2021) demonstrated that combining CO_2 systems with radiative cooling panels reduced peak loads, and Chen et al. (2023) showed that CO_2-based heat pumps with subcooling techniques achieved efficiency gains exceeding

10% compared to R-410A [7,8]. These works underscore the growing viability of CO_2 as a sustainable refrigerant when coupled with auxiliary systems.

Parallel to CO_2 advancements, Earth–Air Heat Exchangers have been widely explored as passive preconditioning systems that exploit the earth's nearly constant subsurface temperature to reduce building heating and cooling loads. Wu et al. (2007) modeled EAHE performance and validated their findings experimentally, while Woodson et al. (2012) confirmed significant temperature reductions in field applications [9,10]. Ghaith and Alsouda (2017) and Baglivo et al. (2018) later showed that coupling EAHE with heat pumps could achieve up to 50% energy savings**,** depending on climate conditions [11,12]. More recent investigations, such as Ramezanpour et al. (2021) and Chiesa et al. (2022), emphasized the potential of EAHE integration in hybrid systems for improving COP and reducing lifecycle emissions in both residential and commercial contexts [13,14].

Despite these advancements, there remains a notable gap in research exploring the coupling of CO_2-based systems with ground-coupled technologies, particularly in configurations designed to maintain subcritical operation under warm climatic conditions. To date, no studies have thoroughly examined the integration of such systems in direct-expansion configurations. Most existing hybrid investigations have focused on combining EAHEs with conventional vapor compression systems utilizing refrigerants such as R-410A or R-134a, rather than CO_2, whose performance is highly sensitive to variations in condensing temperature.

This research addresses this critical gap by proposing a novel hybrid CO_2 Air Conditioning Heat Pump (CO_2-ACHP) integrated with an EAHE to precondition the condenser inlet air. By maintaining the condensing temperature below the critical point through geothermal air pre-cooling, the system transitions CO_2 operation from transcritical to subcritical conditions, significantly improving performance. The novelty of this study lies in combining a natural refrigerant with a passive geothermal system to overcome CO_2's critical temperature limitation, while quantitatively assessing both energy and environmental benefits through a lifecycle perspective.

A mathematical modeling and simulation approach was adopted to evaluate subsoil temperature dynamics in Sydney, Australia, and to predict the EAHE outlet temperature for condenser air pre-cooling. The study is based on numerical simulations, with model outputs validated and benchmarked against data from previous experimental and analytical studies available in the literature. The results demonstrate how the hybrid CO_2-ACHP/EAHE system can enhance the COP, reduce the TEWI, and serve as an environmentally sustainable alternative to synthetic refrigerant-based air conditioning systems.

2. Methodology

The methodology of this study begins with a validated numerical model, followed by a parametric analysis of the EAHE to assess the system's applicability under various operating conditions. For a fair and consistent comparison, the system capacity, compressor type, and heat exchanger configuration were kept identical across all examined cases, including R-410A, transcritical CO_2, and the proposed CO_2-ACHP/EAHE system. According to the Second Law of Thermodynamics, the theoretical efficiency or COP of a reversible thermal process operating between fixed temperature limits is independent of the working fluid's intrinsic properties. However, in practical systems, refrigerant thermophysical properties influence performance due to their impact on real-cycle losses such as pressure drops, heat transfer limitations, and compressor inefficiencies. This distinction clarifies a common misconception in the industry that COP variations arise solely from the refrigerant rather than from cycle design and operational deficiencies. The vapor compression cycle modeled in

This study demonstrates that the system's performance is predominantly influenced by the evaporation and condensation temperatures under equivalent design conditions. The cycle follows the principles of an ideal Carnot cycle, in which the temperature lift between these two states plays a decisive role in determining efficiency. The theoretical COP for the Carnot cycle can therefore be expressed using Equations (1) and (2).

$$COP_{Cooling} = \frac{T_c}{T_h - T_c} \quad \text{and} \tag{1}$$

$$COP_{Heating} = \frac{T_h}{T_h - T_c} \quad , \tag{2}$$

In these equations T_h is the condensing temperature and T_c is the evaporation temperature, temperatures are measured in K.

While the ideal Carnot cycle COP is notably high, it is unattainable in real-life applications due to various cycle losses., such as in the compressor, heat exchanger, refrigerant expansion or because of flow resistance.

These cycle losses can be mitigated by optimizing the compressor type and design, heat exchanger and piping system design, temperature boundaries, and selecting the appropriate expansion device to fit the cycle and refrigerant properties. Optimization involves balancing technical resources and economic considerations.

In the proposed model, air is forced through a pipe buried underground to exchange heat with the surrounding soil. The cooled air is then used to lower the condenser temperature, as illustrated in Figure 1. During the heating season, the outdoor unit functions as an evaporator, and the EAHE reduces the temperature lift, enhancing the system's COP.

The methodology includes the following steps:

1. Estimating Subsoil Temperatures: Subsoil temperatures are estimated at various depths to determine the optimal depth for the project.
2. Calculating Heat Exchanger Outlet Temperature: The heat exchanger outlet temperature is calculated for different pipe lengths.
3. Simulating System COP: The system COP is simulated using CoolPack software to evaluate the impact of EAHE on cycle efficiency [15].
4. Comparative Evaluation: This evaluation includes comparisons with conventional systems operating on a CO_2 transcritical cycle and an R-410A conventional system, considering the complete system performance and lifetime environmental assessment.

The thermophysical properties of carbon dioxide were modeled as temperature-dependent functions to ensure accurate simulation of the vapor compression and heat exchange processes. CO_2 exhibits pronounced variations in its physical properties with temperature and pressure, particularly near its critical point at 30.98°C and 7.38 MPa [16]. These variations significantly influence compressor performance, heat transfer coefficients, and system efficiency in CO_2-based air conditioning and heat pump systems.

In this study, thermodynamic and transport properties of CO_2, including density, specific heat capacity, thermal conductivity, viscosity, and saturation pressure, were obtained using the COOLPack software (Version 1.50) developed by the Technical University of Denmark [17]. The program calculates refrigerant properties based on widely validated correlations and experimental data, offering a convenient platform for evaluating system performance under subcritical and transcritical conditions.

The software covers a temperature range of –50°C to 100°C, which includes the relevant operating envelope for air-conditioning applications.

At subcritical conditions, the liquid density of CO_2 decreases from approximately 1177 kg/m³ at –50°C to 467 kg/m³ near 25°C, while the vapor density rises from 5.6 kg/m³ to 146 kg/m³ over the same range. The specific heat capacity of the liquid phase increases from 1.8 kJ/kg·K at –50°C to about 3.7 kJ/kg·K at 25°C, illustrating the strong temperature dependence near the critical region. Similarly, the thermal conductivity of the vapor phase increases from 0.013 W/m·K at –50°C to 0.032 W/m·K at 100°C, while the dynamic viscosity rises from 12 µPa·s to 22 µPa·s [17]. The saturation pressure increases exponentially from 0.52 MPa at –50°C to 7.38 MPa at 30.98°C, defining the subcritical–transcritical transition range.

For integration into the simulation model, the COOLPack outputs were fitted to temperature-dependent polynomial correlations, providing computational efficiency in iterative calculations of heat transfer and cycle performance. This approach ensured consistent thermodynamic input data across all simulations, including those comparing R-410A, transcritical CO_2, and the proposed CO_2–ACHP/EAHE configuration. The strong temperature dependence of CO_2's thermophysical properties highlights the necessity of maintaining condensing temperatures below the critical point, which is a key objective of the proposed EAHE integration strategy. This allows the system to operate within the high-efficiency subcritical regime, enhancing overall COP and reducing environmental impact.

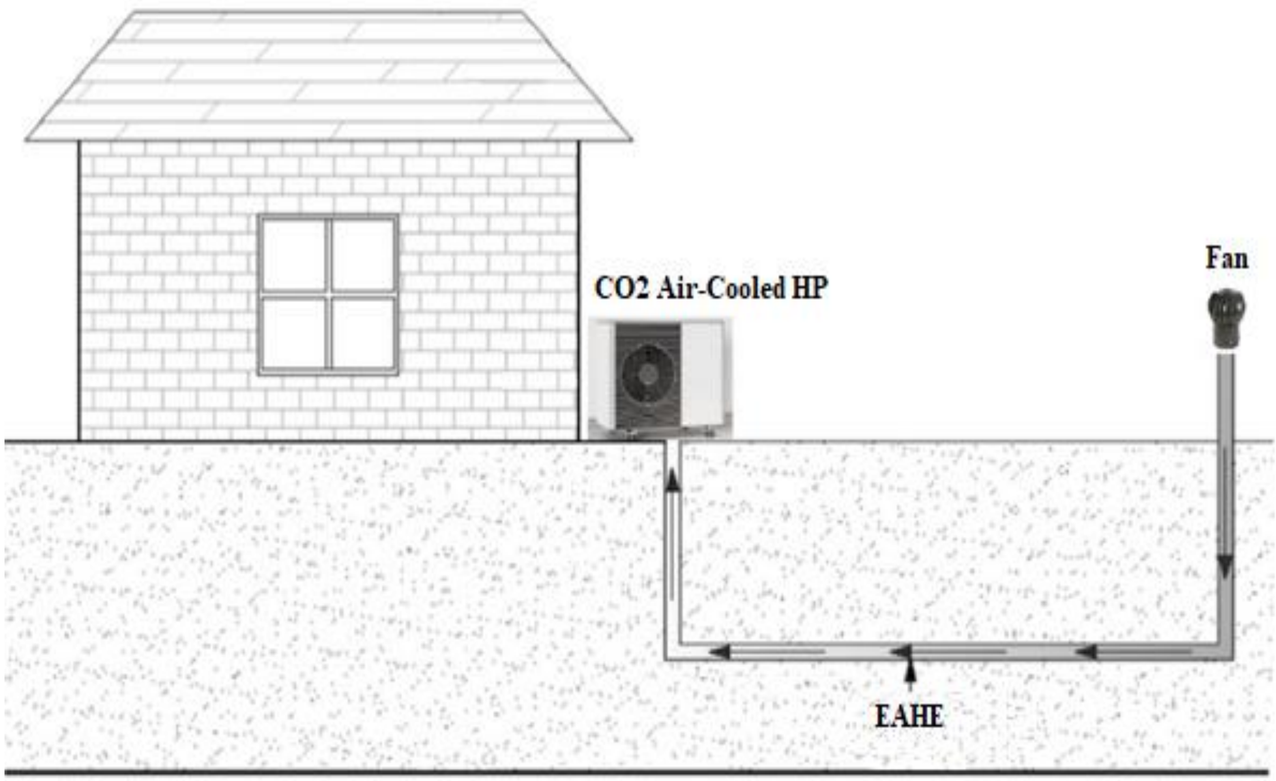

Figure 1. Integrated CO_2 air conditioner/EAHE model

2.1 Mathematical Model

The EAHE is one of the simplest heat exchangers to design. However, it is essential to establish design goals before the design stage, which may include, maximizing air-to-ground temperature exchange, achieving the highest thermal performance, or minimizing pressure drop along the pipe. In this research, the primary design goal is to optimize the condenser heat dissipation and maintain it below the critical temperature of CO_2, which necessitates removing a specific amount of heat based on the system's capacity. To evaluate the performance of the EAHE, the subsoil temperature must first be estimated. This temperature can then be used in heat transfer calculations to determine the heat exchanger's outlet temperature.

2.1.1 Sub-soil temperature estimation

The EAHE system was modeled using mathematical calculations and Excel simulations to determine the subsoil temperature at various depths below the ground surface. This approach also facilitated the calculation of the EAHE outlet air temperature for different pipe lengths and depths. Given that subsoil temperature is primarily influenced by climate conditions and soil properties, Sydney, Australia, was selected as the study location. Australia is divided into six climate zones, with Sydney situated in the temperate climate zone, as illustrated in Fig.2. This zone experiences mild to hot and humid summers and moderately cold winters without a distinct dry season. The insights from this study apply to any location with similar climatic conditions and soil properties.

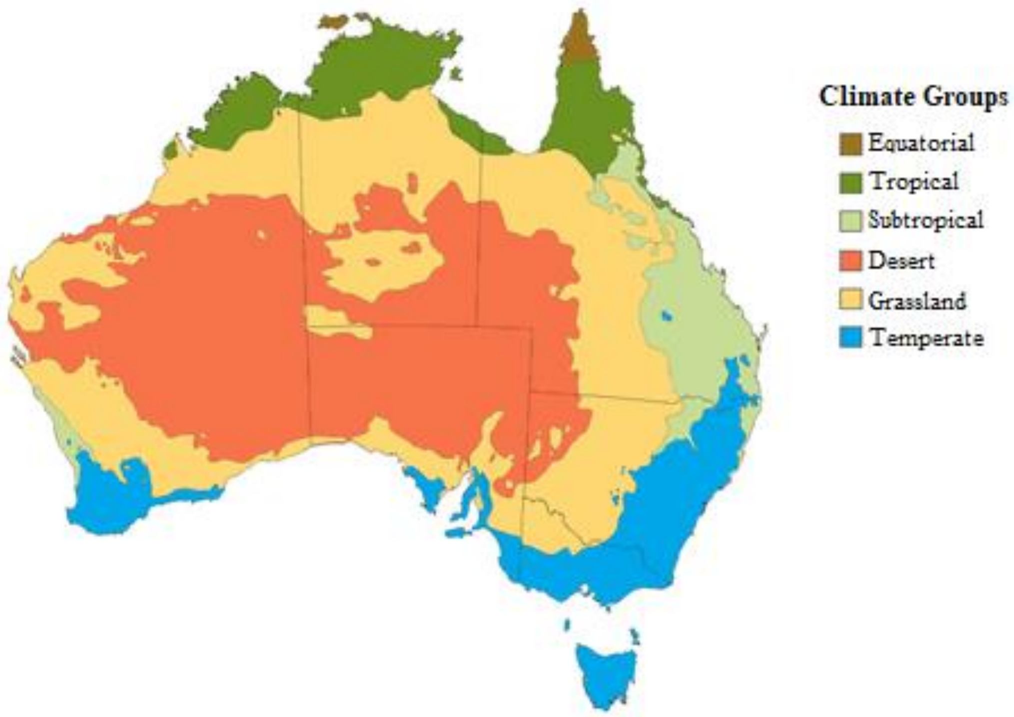

Figure 2. Australia Climate Zone [18]

The subsoil temperature is influenced by the thermal properties of the soil and its moisture content. However, the primary determinant of subsoil temperature is soil diffusivity, which hinges on factors such as soil thermal conductivity, density, and thermal capacity, as outlined in Equation 3,

$$\alpha = \frac{\lambda_{soil}}{C_p \cdot \rho_{soil}}, \tag{3}$$

Thermal diffusivity is a measure of a material's ability to conduct thermal energy relative to its capacity to store it. It defines how quickly heat can penetrate a material when a temperature gradient exists.

Mathematically, thermal diffusivity is expressed as the ratio of thermal conductivity to the product of density and specific heat capacity. In the context of soil, higher thermal diffusivity indicates that temperature changes in the surface layers are transmitted more rapidly to the subsoil. This property depends on the soil's composition, compactness, and moisture content, as water significantly enhances both thermal conductivity and heat capacity. Thus, soil with high moisture content and greater density tends to exhibit higher thermal diffusivity, enabling more efficient heat transfer to deeper layers (Hillel, 2004). [19]

The calculation of subsoil temperature relies on the principles of conductive heat transfer theory and the energy balance equation established by Labs & Harrington in 1982. Equation 4 defines the subsoil temperature as a function of the depth of the Earth-Air Heat Exchanger [20].

$$T_{(z,t)} = T_m - A_s e^{-z\sqrt{(\frac{\pi}{8760\alpha})}} \cos\left[2\frac{\pi}{8760} * \left(t - t_{\circ} - \frac{z}{2}\sqrt{\frac{8760}{\pi\alpha}}\right)\right] \quad (4)$$

where $T_{(z,t)}$ Is the subsoil temperature in °C related to depth and time of the year, T_m is the ambient annual mean temperature, A_s is the amplitude of the surface temperature annual chart, α is the soil diffusivity in (m²/s) and t_o is the phase constant, which is identified as the time of year in hours of the minimum surface temperature. A_s= 1.1+A, where A is the amplitude of the daily mean temperature around the year,

$$A = \frac{(\max mean\ daily\ temperature - \min mean\ daily\ temperature)}{2} \quad . \quad (5)$$

The phase constant, identified as the time of the minimum surface temperature within a year, has been extensively examined by various researchers. It's typically observed to occur approximately 30-45 days after the coldest day of the year. This lag in surface temperature is attributed to the Earth's thermal inertia, which varies across locations due to differences in surface types and soil properties [21]. In the case of Sydney, where the coldest day typically falls around 18 July based on weather data spanning the past five decades (as depicted in Fig.3), the phase constant was determined to be 6600 hours.

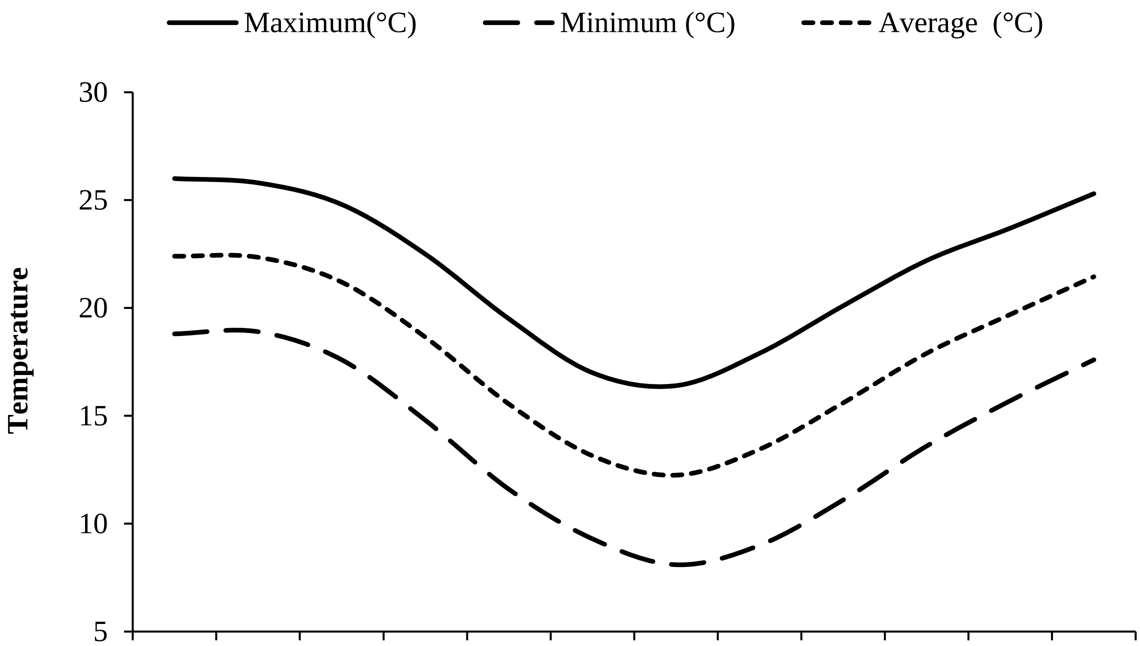

Figure 3. Monthly mean temperature for Sydney, Australia [19]

2.1.2 Heat Exchanger Calculations

In the pursuit of optimizing the efficiency of This system's condenser, valuable insights are provided by simulation software regarding the dissipated heat amount. Additionally, adherence to recommended airflow velocities within external ducts and pipes ranging from 9 to 11 (m/s) enables the determination of the requisite pipe diameter [22]. This pivotal endeavour is poised to enhance the performance and efficacy of This system through meticulous attention to airflow dynamics and thermal management. Given that the simulation software provides the amount of heat dissipated by the condenser and recommends an airflow velocity through external ducts and pipes ranging from 9 to 11 (m/s), the required pipe diameter can be determined using the following formula [23]:

$$Air\ Flow = CSA * V_{air} \ , \tag{6}$$

$$\text{Then, } D = \sqrt{(4 * \frac{CSA}{\pi})} \ , \tag{7}$$

$$\mathrm{Re} = \frac{\mathrm{Vd}}{\nu}. \tag{8}$$

According to Blasius formulas for single phase pressure drop in channels and as 100,000<Re<3,000,000, friction factor f can be calculated through the following formula [23]:

$$\mathrm{f} = 0.0032 + \frac{0.221}{\mathrm{Re}^{0.237}} \ , \tag{9}$$

$$\Delta P_{f} = \frac{1}{2}\frac{f\rho V^2}{d_e} \quad (Pa/m) \ , \tag{10}$$

$$\Delta P_{f}(total) = Equivalent\ length\ \times \Delta P_{f} \ , \tag{11}$$

$$P_T = P_V + P_f \ , \tag{12}$$

$$P_V = \rho V^2/2, \tag{13}$$

$$Fan\ power = P_T \dot{V}/\eta \quad , \tag{14}$$

The heat transfer of the EAHE can be calculated using the heat transfer equations provided in Eq. (15) to Eq. (26) [24]. Based on the calculations and assuming the flow is fully developed and turbulent, the Dittus-Boelter equation will be applied. The Dittus-Boelter equation is applicable for calculating the heat transfer coefficient in turbulent flow within smooth, circular pipes, specifically when the flow is fully developed and the fluid is in the turbulent regime. It is typically used when the Reynolds number (Re) is greater than 10,000, with an ideal range between 10,000 and 100,000. The equation assumes that the fluid properties, such as viscosity, thermal conductivity, and specific heat, remain constant over the temperature range of interest. Additionally, it is most accurate for single-phase fluids (either liquid or gas) and for flow in smooth pipes, where surface roughness is negligible. The equation is applied in regions of the pipe where the thermal boundary layer is fully developed, usually after the entrance length. It is commonly used in heat exchanger design, particularly for estimating the convective heat transfer coefficient in forced convection. The Dittus-Boelter equation is expressed as:

$$Nu = 0.23Re^{0.8}\, Pr^{n} \tag{15}$$

n= 0.4 for T (wall) >T(fluid), n=0.3 for T (wall) <T(fluid)

The convective heat transfer coefficient h can be expressed as:

$$h = \frac{Nu.K_{Air}}{D} \tag{16}$$

Wall resistance:

$$R_w = \frac{d_i}{2K_w}\ln(\frac{d_o}{d_i}) \tag{17}$$

The thermal resistance due to convective heat transfer on the pipe's inner surface can be obtained as

$$R_c = \frac{1}{h.A_{in}} \tag{18}$$

Where $A_{in}$the pipe is the inner surface area and can be expressed as

$$A_{in} = 2\pi L r_{in} \tag{19}$$

Soil thermal resistance:

Assuming a soil annulus of equal to 2r will give a thermal resistance of the soil annulus as

$$R_{soil} = \frac{\ln(^{2r}/_{r})}{2\pi L K_{soil}} \tag{20}$$

$$R_{total} = R_w + R_c + R_{soil} \tag{21}$$

Overall heat transfer coefficient U can be expressed as

$$U = \frac{1}{R_{total}} \tag{22}$$

As the air can be considered the fluid with the lower ($\dot{m}C_p$) Value, then the number of heat transfer units (NTU) can be presented as:

$$NTU = \frac{UA}{\dot{m}Cp_{Air}} \tag{23}$$

$$C_r = \dot{m}Cp_{Air}/\dot{m}Cp_{Soil} \tag{24}$$

The heat exchanger effectiveness Ɛ can be expressed by the following formula reported by Harms et al. for cross-flow heat exchangers with one fluid unmixed. This formula is valid only when the Cr value is equal or close to zero.

$$\varepsilon = 1 - e^{(UA/mCp)} \tag{25}$$

Through the effectiveness value, the EAHE outlet temperature can be calculated as:

$$T_{Out} = T_{ambient} - \varepsilon(T_{ambient} - T_{subsoil}) \tag{26}$$

To calculate the fan power required to push the air through the EAHE, the dynamic and static pressure need to be obtained using the below formulas (27-30) [23]:

$$P_T = P_V + P_S \tag{27}$$

$$P_V = \rho V^2/2 \tag{28}$$

$$P_S = f\rho V^2/2D \tag{29}$$

$$Fan\ power = P_T \dot{V}_{/\eta} \tag{30}$$

2.1.3 Equations Governing the Air Conditioning Cycle

The performance of the vapor compression cycle is evaluated using Equations (31–35) [25]. The rate of heat absorbed by the evaporator can be calculated using Equation (31).

$$q_{eva} = \dot{m}.h_{fg} + \dot{m}\ C_{p.v}\Delta T_{sup} \tag{31}$$

This heat is equivalent to the heat transferred to the fluid when using a heat transfer medium fluid, as represented in eq.32.

$$q_{fluid} = \dot{m}_{fluid} C_p \Delta T_{fluid}, \quad (32)$$

ΔT_{fluid} is the temperature difference of the heat transfer fluid across the heat exchanger. Similarly, the rate of heat dissipated to the surroundings or the heat transfer fluid through the condenser can be represented by eq. (3).

$$q_{con} = -(\dot{m}. h_{fg} + \dot{m}\, C_{p.l} \Delta T_{sub}), \quad (33)$$

The compressor power can be expressed by the enthalpy difference across the compressor with consideration of the mechanical efficiency as in eq. (34).

$$W_{comp} = \dot{m_{ref}}. (h_{con} - h_{eva}). \frac{1}{\eta_{mec}}, \quad (34)$$

The opposite process of the compression is the expansion process, which is essential for the VCC to operate, as it is required to reduce the refrigerant pressure to allow the refrigerant to evaporate at a lower cycle pressure; the net rate of energy wasted through the expansion device can be estimated by eq. (35)

$$E_{exp=}\left(W_{comp} + q_{eva}\right) - q_{con}, \quad (35)$$

2.1.4 Cycle Environmental Impact Calculations

The cycle environmental impact and energy consumption analysis is based on Eq. (36-38) [26].

$$TEWI = N[(GWP * L) + (E_c * \beta)] \quad (36)$$

(N is the system's expected lifetime as the number of years, L is the annual refrigerant leakage, E_c is the system energy consumption, and β is the carbon dioxide emission factor calculated by CO_2 emitted/kWh.) β = 0.73 in NSW [26].

$$EER = 3.41214 * COP \quad (37)$$

$$SEER = EER*(1 + (Tc - To)/100) \quad (38)$$

The lifetime energy consumption and environmental impact are determined by equations (36-38). The following assumptions have been made: the system is a 15kW light commercial system used consistently for eight hours a day and twenty-six days a month during five months (November to March) of the cooling season and five months (May to October) of the heating season. The system's expected lifespan is 15 years, with an average annual refrigerant leak rate of 10% and a refrigerant charge of 3.3kg. Additionally, considering the system's operation in Sydney, Australia, the carbon dioxide index is assumed to be 0.73.[27]

To ensure consistency and simplify the computational model, several assumptions were made in the analysis. The soil surrounding the EAHE pipe was assumed to be homogeneous, with uniform thermal and physical properties in all radial directions. The EAHE pipe wall was considered to be uniform in both material and dimensions, providing a consistent heat transfer interface along the entire pipe length. Air circulation through the EAHE was achieved using a dome-type, push-through blower with an efficiency of 80%, representing typical performance for ventilation-grade fans in underground ducts. For all evaluated systems, cross-flow heat exchangers were adopted for both the evaporator and condenser, ensuring comparable heat transfer characteristics across different configurations. The isentropic efficiency of the compressor was assumed to be 77% for all cycles, in accordance with typical performance data for medium-capacity CO_2 and R-410A compressors. These assumptions provide a uniform baseline for performance comparison and facilitate the evaluation of thermodynamic and environmental parameters under equivalent design conditions.

3. Results and Discussion

The thermal properties of soil in Sydney region were investigated through laboratory tests, revealing values of 2,436 kg/m³ for soil density, 1.33 W/m.K for soil thermal conductivity, and 723.4 J/kg.K for specific heat [21]. Subsequently, soil thermal diffusivity was computed and determined to be 0.0027 m²/h. By employing the energy balance equation and heat transfer theory Eq.2 within the mathematical model, subsoil temperatures were calculated for various depths under Sydney's weather conditions and soil properties, as summarized in Table 1. The analysis demonstrates that subsoil temperature varies with depth, exhibiting distinct peak values and peak times. As depth increases, temperature stability improves, consistent with the expectation that soil acts as thermal insulation between deeper layers and the surface. The observed lag in peak time also increases with depth, influenced by the Earth's thermal inertia, as illustrated in Fig. 4.

Furthermore, it was observed that beneath the ground surface, temperature fluctuations relative to ambient temperature diminish, culminating in stability around 4.0 m depth throughout the year. This phenomenon underscores the role of soil as a moderating buffer against external temperature variations, highlighting its importance in thermal regulation.

Table 1. Subsoil temperature at different depths around the year

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
(T,0.5m)	22.3	22.5	21.5	19.5	17.1	14.9	13.4	13.1	14.0	15.9	18.3	20.6
(T,1.0m)	21.1	21.8	21.4	20.0	18.1	16.1	14.6	13.8	14.2	15.4	17.3	19.3
(T,1.5m)	20.2	21.0	21.0	20.1	18.7	17.0	15.5	14.6	14.6	15.4	16.8	18.5
(T,2.0m)	19.4	20.3	20.6	20.1	19.0	17.6	16.3	15.3	15.0	15.5	16.5	17.9
(T,2.5m)	18.8	19.7	20.1	19.9	19.2	18.1	16.9	16.0	15.5	15.7	16.4	17.4
(T,3.0m)	18.3	19.2	19.7	19.7	19.2	18.4	17.4	16.5	16.0	15.9	16.3	17.2
(T,3.5m)	17.9	18.7	19.2	19.4	19.1	18.5	17.7	17.0	16.4	16.2	16.4	17.0
(T,4.0m)	17.7	18.3	18.9	19.1	19.0	18.6	18.0	17.3	16.8	16.5	16.5	16.9
(T,4.5m)	17.5	18.1	18.6	18.9	18.9	18.6	18.2	17.6	17.1	16.7	16.7	16.9
(T,5.0m)	17.4	17.9	18.3	18.6	18.7	18.6	18.2	17.8	17.3	17.0	16.9	17.0
(T,6.0m)	17.3	17.6	17.9	18.2	18.4	18.4	18.3	18.0	17.7	17.4	17.2	17.2
(T,7.0m)	17.4	17.5	17.7	18.0	18.1	18.2	18.2	18.1	17.9	17.7	17.5	17.4
MAT	22.8	22.6	21.3	18.7	15.6	13.2	12.3	13.5	15.6	17.9	19.7	21.5

As detailed in the methodology section, the implementation of EAHE technology in this project serves the purpose of maintaining the condenser temperature below 31.98°C while ensuring a sufficient flow rate to dissipate the heat generated by the condenser. Consequently, the subsoil temperature must deviate from the target temperature of 31.98°C to facilitate heat transfer within the EAHE system. To align with the research objectives, a depth of 2.5 m was chosen due to its favorable temperature stability throughout the year, characterized by a temperature range of 15.5°C to 20.1°C. Although Sydney's monthly mean air temperature fluctuates between 12.5°C to 22.8°C, the summer months experience high daily temperatures, reaching the mid to high thirties. Utilizing the EAHE system ensures a more consistent temperature profile year-round, mitigating daily temperature fluctuations. The amplitude of subsoil temperature changes with depth, alongside variations in lag time relative to ambient temperature. As depicted in Fig. 4, the amplitude ranged from 9.4°C at 0.5 m depth to 2.2°C at 4.5 m depth. Additionally, the lag time increased from approximately 40 days at 0.5 m to around 120 days at 4.5 m. This dynamic could enhance EAHE performance at greater depths, providing colder subsoil temperatures during summer and warmer temperatures in winter. However, the marginal temperature variation at greater depths, such as 2.2°C at 4.5 m, warrants consideration during EAHE design, particularly in specific applications and design objectives. Non-technical factors, including financial considerations such as capital expenditure (CAPEX) and operational costs (OPEX), alongside surface characteristics, such as the absence of grass in this study, must also be factored into EAHE depth determination.

Furthermore, the heat dissipation analysis revealed a heat output of 18.2 kW from the condenser, aligning with expectations given typical heat dissipation rates exceeding evaporator coil capacities due to heat absorbed by the evaporator and heat added by the compressor. It should be highlighted that the heat dissipation from the condenser was considered at its maximum value when the system is running at full capacity while it could be less than that through most of the cooling season which will enhance the system's efficiency.

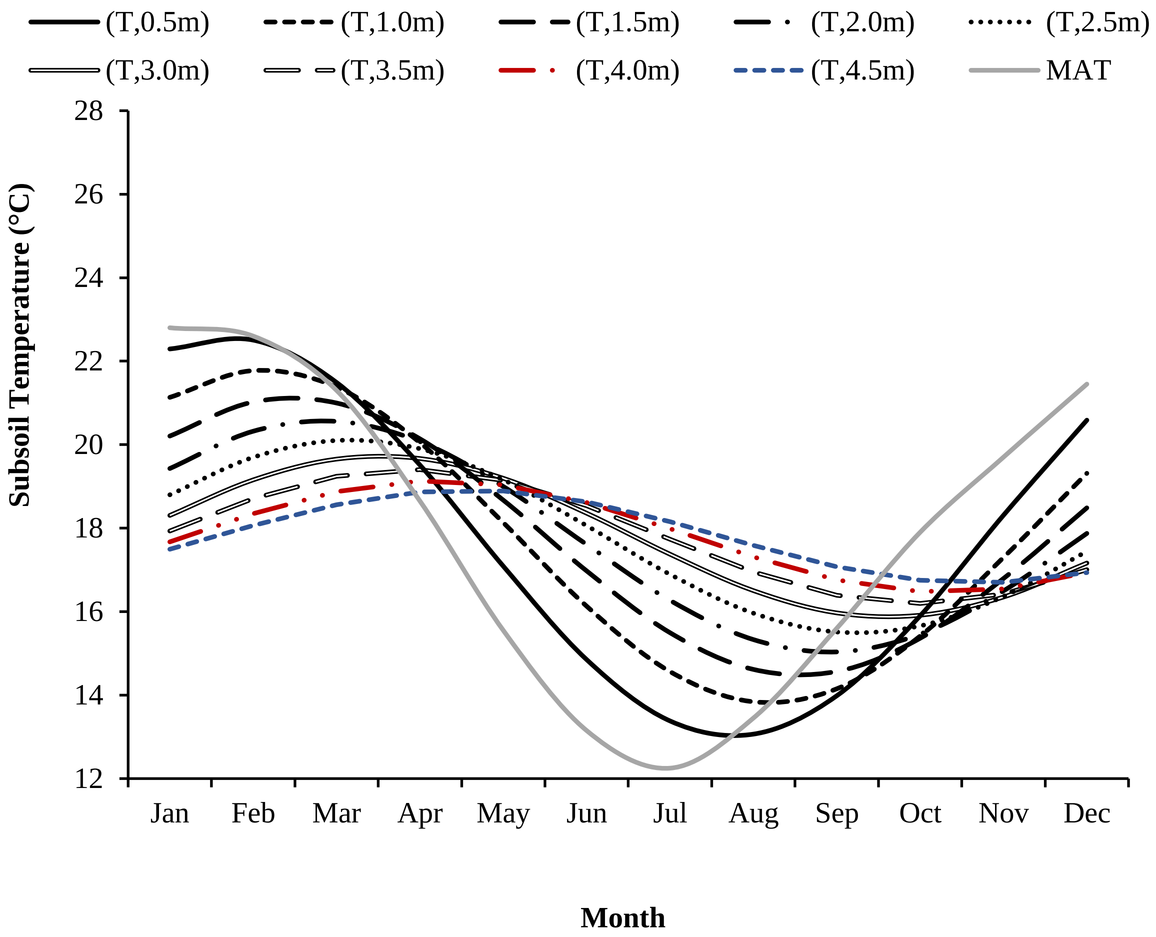

Figure 4. Subsoil temperature variation around the year on different depths

The EAHE outlet temperature was analyzed across varying pipe lengths, as depicted in Fig. 5. Notably, the temperature exhibited a declining trend with increasing pipe length before stabilizing around 40 m. This stabilization coincided with the heat exchanger effectiveness nearing close to 100%, as illustrated in Fig. 6. Thermodynamic tables were instrumental in acquiring air thermal properties, referenced at the mean air bulk temperature of the EAHE. A conservative assumption of 20°C was initially made for the outlet temperature, considering the relatively minor sensitivity of air thermal properties to slight temperature fluctuations. Subsequently, calculations were refined using the precise outlet temperature obtained from the EAHE, enabling accurate determination of air thermal properties from the tables. Interpolation techniques were employed to extract data, as outlined in Table 2.

Table 2. Air Thermal Properties at Bulk Mean temperature [24]

T (C°)	**Cp (kJ/kg. K)**	**μ (kg/m. s)**	**ρ (kg/m³)**	**K (W/m. K)**	**Pr**	**ν(m²/s) x10^{-5}**
20	1007	1.825×10^{-5}	1.204	0.02514	0.7309	1.516
25	1007	1.849×10^{-5}	1.184	0.02551	0.7296	1.562
30	1007	1.872×10^{-5}	1.164	0.02588	0.7282	1.608

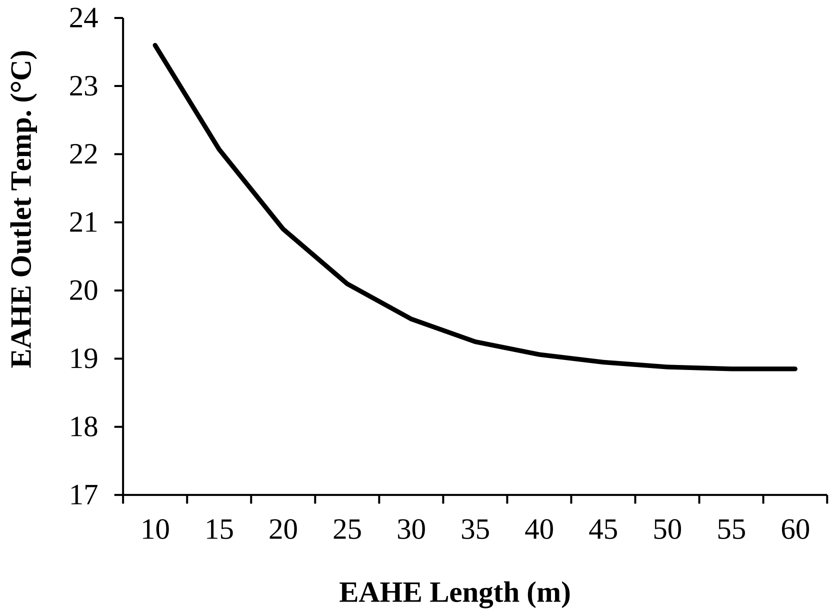

Figure 5. EAHE outlet temperature relation with EAHE length

The heat exchanger's effectiveness is influenced by several factors, including the heat transfer area, fluid flow rate, thermal capacity of fluids or materials, and thermal resistance of pipe material. In this scenario, increasing the pipe length augments the heat transfer area, consequently enhancing heat transfer to the air and elevating the heat exchanger's effectiveness, as depicted in Fig. 6. The EAHE demonstrates a notable increase in effectiveness, reaching 94% around 35 m, with optimization achieved at approximately 60 m, where effectiveness approaches 100%. This signifies a state where negligible heat transfer occurs between the two sides of the heat exchanger. Ideally, the optimal length is when the heat exchanger's effectiveness is maximized. However, practical considerations, including project feasibility and cost-effectiveness, necessitate a balanced approach in selecting the appropriate length. Therefore, EAHE length is typically chosen to meet project objectives efficiently while considering technical benefits and cost implications. Finding the optimal length entails striking a balance between technical performance and economic viability, ensuring the achievement of project goals while maintaining feasibility.

While increasing the pipe length enhances the thermal efficiency of the EAHE, the improvement follows a diminishing-return trend beyond a certain point. The relationship between pipe length and effectiveness is nonlinear; as the length increases, each additional meter contributes progressively less to heat transfer. The effectiveness curve becomes asymptotic as it approaches 100%, indicating that further length extensions yield negligible thermal benefits. From an economic standpoint, the additional cost of longer piping, materials, and installation must be weighed against these marginal gains. In this study, a 35-meter pipe was selected as an optimal compromise, offering approximately 94% effectiveness while maintaining economic feasibility compared to a 60-meter configuration that achieves near-maximum effectiveness.

The choice of pipe material also significantly influences system performance. PVC was adopted in this study due to its favorable cost-performance balance, corrosion resistance, and ease of installation. However, its relatively higher thermal resistance compared to metals may slightly limit heat transfer, particularly under high load or variable soil conditions.

Long-term EAHE performance is also influenced by soil moisture content and seasonal temperature variability. Moist soils generally enhance heat transfer due to their higher thermal conductivity, whereas dry soils increase thermal resistance and reduce overall effectiveness. Seasonal variations cause fluctuations in subsoil temperature profiles, with the most pronounced effects occurring near the surface. However, at the studied burial depth of 2.5 meters, the soil temperature remains relatively stable throughout the year, mitigating seasonal impacts and supporting consistent system performance [21]. Over time, transient conditions such as changes in moisture distribution, rainfall patterns, or groundwater movement can slightly alter thermal conductivity, but these variations are minor compared to the stability of deeper soil layers.

The worst-case scenario in this study, with an outlet temperature of 19.8°C under an ambient temperature of 36°C, demonstrates that the system maintains acceptable performance even during peak summer conditions. This conservative design approach ensures that the EAHE continues to deliver reliable condenser air pre-cooling and energy savings throughout the year, accounting for both environmental variability and practical cost considerations.

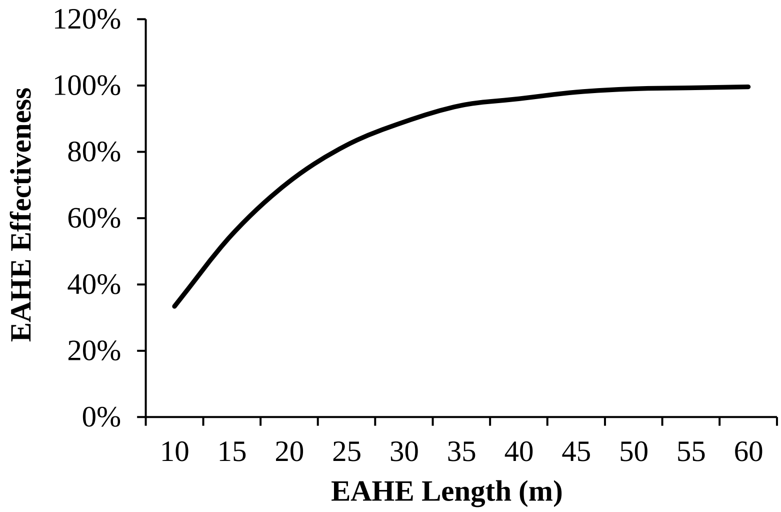

Figure 6 Change in EAHE effectiveness with pipe length

Furthermore, Fig. 7 demonstrates that the variation in EAHE outlet temperature remained minimal despite fluctuations in inlet air temperature. Spanning from 8.2°C to 36°C to encompass potential temperature ranges for Sydney, the EAHE outlet temperature exhibited a modest fluctuation of only 1.7°C. Specifically, it ranged from 18.1°C with an air temperature of 8.2°C to 19.8°C with an air temperature of 36°C. This minimal variation in outlet temperature indicates a robust and stable performance of the EAHE system, ensuring consistent thermal output despite significant changes in inlet air temperature. Such stability is crucial for maintaining the efficiency and reliability of the system under varying environmental conditions.

Additionally, the calculated external diameter of the pipe at 500mm, designed to accommodate the required airflow and condenser heat dissipation rate while maintaining a velocity of 12 m/s, highlights the careful consideration of fluid dynamics and thermal management in the system design. This dimension not only ensures the efficient operation of the EAHE but also aligns with the technical requirements to achieve the desired thermal performance and airflow characteristics. By balancing thermal efficiency with practical considerations such as pipe diameter and airflow velocity, the system design demonstrates a comprehensive approach to optimizing both performance and feasibility.

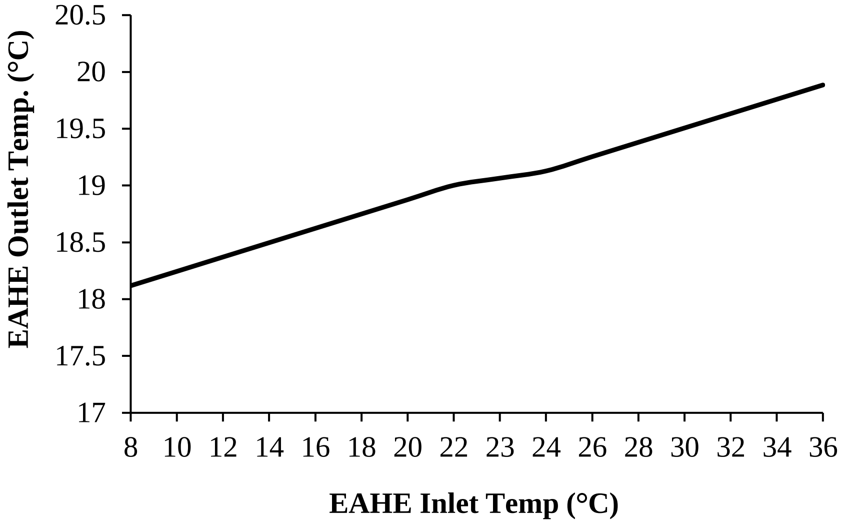

Figure 7. EAHE Outlet Temperature Variation with Inlet Temperature

The static pressure of the Earth-Air Heat Exchanger was thoroughly examined due to its critical role in dictating fan selection and ultimately influencing the EAHE's suitable length and the overall system's COP. Fig. 8 illustrates the linear relationship between the EAHE and the pressure drop, encompassing both static and dynamic components. Additionally, it demonstrates the direct correlation between fan power and dynamic and static pressure, as depicted in Fig. 8 and detailed in equations (9-12). It's important to note that the pressure drop in the EAHE is influenced by various factors, such as fluid velocity, fluid viscosity, and the internal surface roughness of the pipe. The difference in the slope between the pressure drop and the fan power is attributed to the fan's total efficiency, encompassing mechanical and electrical efficiency components. Understanding and optimizing these parameters are crucial in designing an efficient and effective EAHE system.

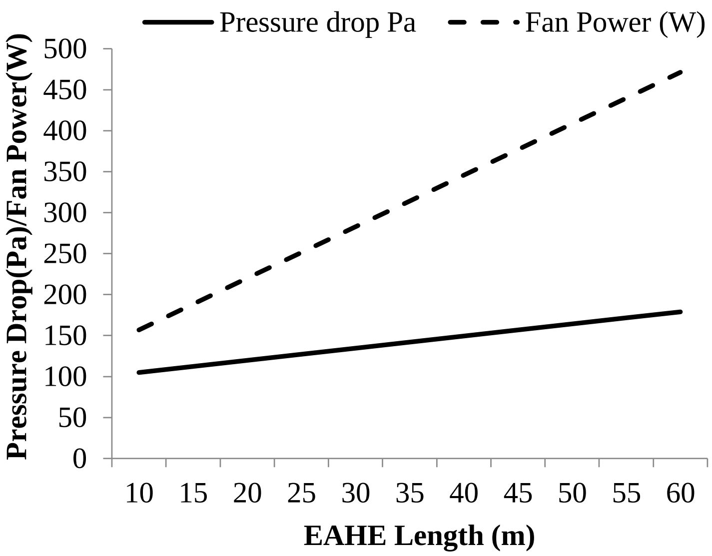

Figure 8. The impact of EAHE length on the pressure drop and fan power

Figures 9 and 10 illustrate the simulated velocity distribution and flow streamlines through the EAHE pipe, which has a diameter of 500 mm and a total length of 35 m. The contour plot (Figure 9) depicts the parabolic velocity profile typically observed in transitional pipe flow, where the maximum velocity occurs along the pipe centerline and decreases progressively toward the wall due to frictional resistance. This velocity distribution strongly influences the convective heat transfer between the air and the pipe wall, with the near-wall region governing the overall thermal exchange rate with the surrounding soil. The streamline representation (Figure 10) provides insight into the axial flow development along the pipe length, confirming that air moves steadily through the pipe with negligible radial disturbance, thereby validating the one-dimensional flow assumption used in the analytical model. The relatively uniform velocity field along the pipe length also indicates stable flow behavior, which supports consistent thermal interaction with the subsoil. This flow pattern is essential for predicting the air outlet temperature and assessing the overall heat exchange efficiency of the EAHE when integrated with the CO_2 air-conditioning heat pump system.

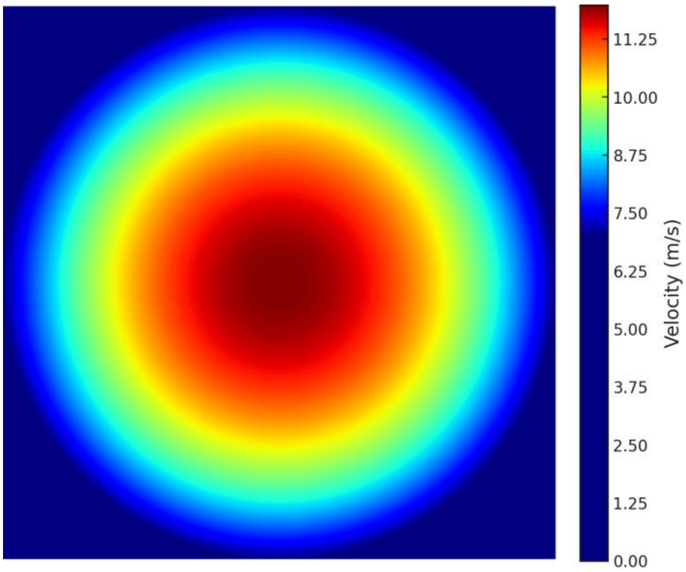

Figure 9 EAHE Velocity Contour

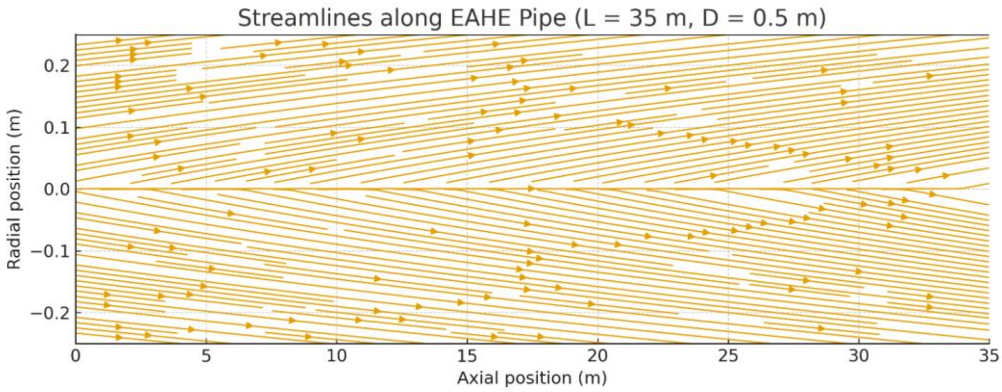

Figure 10 The Flow Streamline Along the EAHE

This study utilized CoolPack simulation software to assess the performance of three distinct cycle options. A 15-kW cycle was established with evaporation and condensing temperatures set at 5°C and 45°C, respectively, aligning with the requirements for direct expansion building cooling applications. Given the inclusion of CO_2 as one of the selected refrigerants, it becomes imperative, from an engineering standpoint, to employ a supercritical or transcritical process. This ensures operation within a rational temperature range due to CO_2's relatively low critical temperature. The transcritical cycle, depicted in Fig. 11, represents an alternative to the more common subcritical cooling cycle. The primary distinction lies in the critical point of the refrigerant utilized.

In a typical refrigeration cycle, the refrigerant undergoes phase changes between liquid and vapor states. The critical point denotes the temperature and pressure at which these phases coexist. In contrast, in a transcritical cycle, the refrigerant operates at pressures and temperatures surpassing its critical point. Consequently, the refrigerant does not fully condense into a liquid; instead, it undergoes a pseudo-boiling process, transitioning between liquid and gas phases without a distinct phase change. The expansion valve in a transcritical cycle assumes a critical role in regulating the refrigerant pressure as it traverses the system, facilitating efficient operation within the transcritical regime.

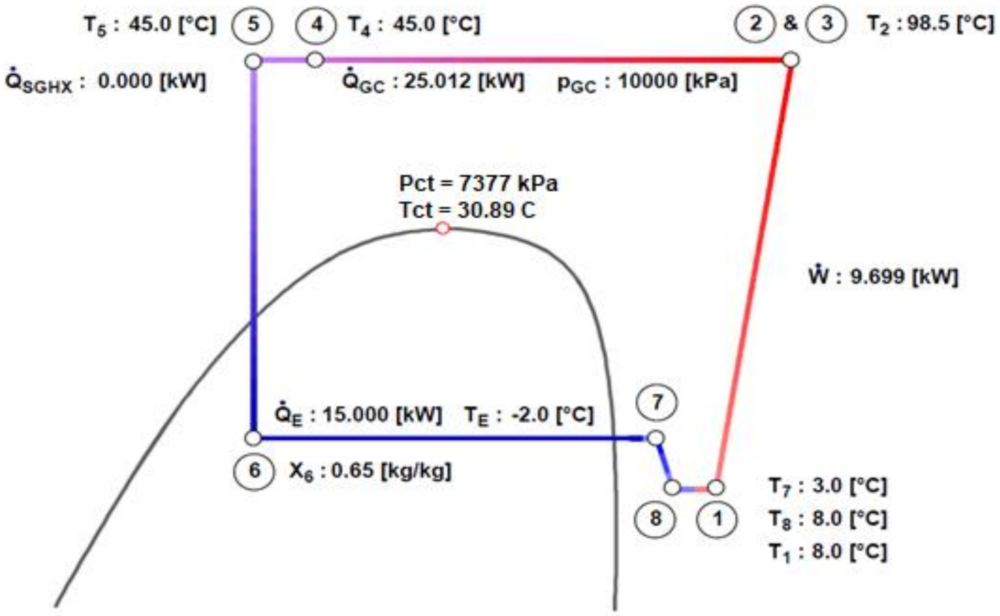

Figure 11. CO_2 transcritical cycle

As outlined in the methodology section, in the ideal cycle, the refrigerant properties do not directly influence the cycle COP. Instead, any efficiency loss within the system stems from energy losses inherent to the cycle itself. In the case of the CO_2 cycle, it's noteworthy that the compressor power demand is relatively high, totaling 9.699 kW. Consequently, the COP of the CO_2 transcritical cycle is measured at 1.547, a value considered low compared to other refrigerants. This disparity is illustrated in Fig. 12, which depicts the schematic of R-410A operating within the same temperature range and with an equivalent cooling capacity. Notably, the compressor work for R-410A constitutes approximately 44.5% of what the CO_2 transcritical cycle requires. A significant portion of the energy loss in the transcritical cycle occurs during the compression and expansion stages. Previous research has indicated that expansion losses are contingent upon the ratio between the specific heat capacity of the refrigerant in its liquid state and the latent heat of vaporization. For R-744 (CO_2), this ratio is approximately 2.5 times that of R-410A, as reported by Lorentzen in 1994. Consequently, R-744 experiences more pronounced expansion losses compared to R-410A [28].

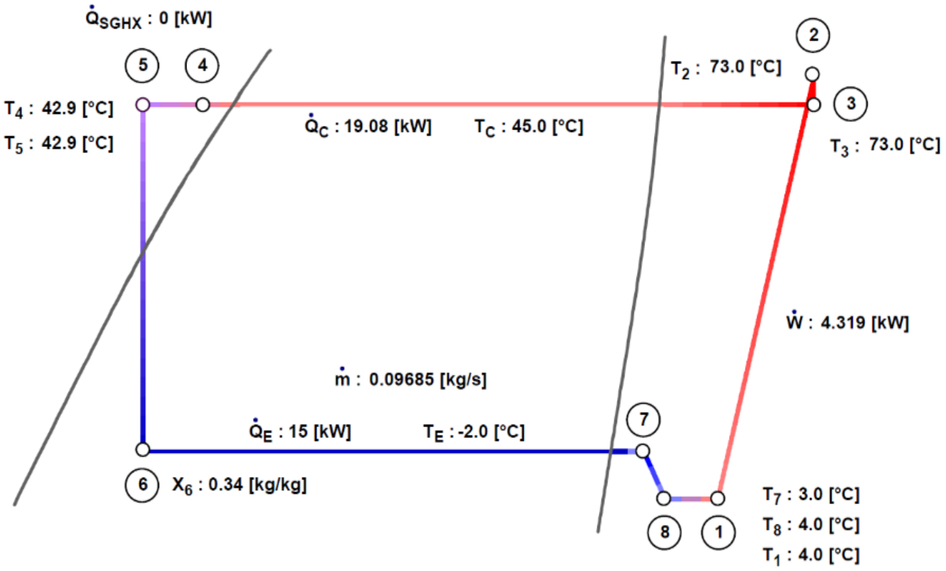

Figure 12. Conventional cycle operating with R-410A

When integrating the system with an EAHE as a complete hybrid system, the CO_2 refrigerant can operate within the conventional subcritical refrigeration cycle. This obviates the necessity to utilize the lower COP transcritical cycle. This is feasible by maintaining the condensing temperature below the critical temperature of CO_2, as depicted in Fig. 13. The figure illustrates the schematic of the CO_2 cycle operating between 4°C evaporating and 30°C condensing temperatures, delineating the cycle parameters and the operating temperature range. This approach allows for efficient operation within the subcritical regime, ensuring optimal performance while leveraging the advantages of CO_2 as a refrigerant.

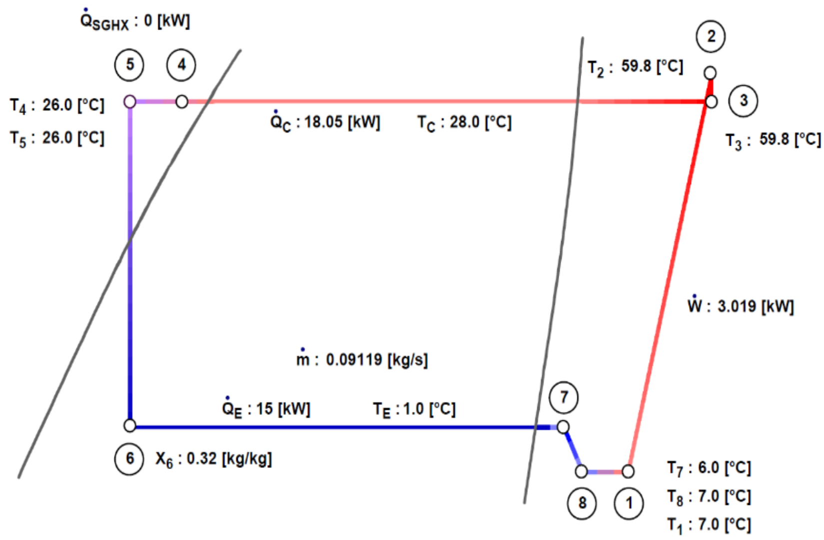

Figure 13. CO_2 cycle operating at 30°C condensing temperature

Before comparing the COP of these three cycles and assessing the advantages of integrating the system with an EAHE, adjustments were made to the calculations. This involved incorporating the power consumption of the EAHE fan, as detailed in Table 3, based on the fan power obtained from Fig. 8 for a 35-m EAHE length, estimated to be approximately 300W. This adjustment ensures a comprehensive evaluation of the system's overall energy consumption and efficiency, considering all relevant components.

Table 3. Cycle COP for different cycle options

Cycle Option	Compressor Power (kW)	EAHE Fan Power (kW)	Condenser Capacity (kW)	Evaporator Capacity (kW)	COPc
Cooling					
R-410A	4.319	-	19.08	15	3.47
CO_2 Transcritical	9.699	-	25.012	15	1.55
Hybrid CO_2/EAHE	3.019	0.3	18.05	15	4.52
Heating					
Cycle Option	**Compressor Power (kW)**	**EAHE Fan Power**	**Condenser Capacity (kW)**	**Evaporator Capacity (kW)**	**COPh**
R-410A	4.319	-	16.02	14	3.71
CO_2Transcritical	2.938	-	16.95	14	5.77
Hybrid CO_2/EAHE	2.128	0.3	16.28	14	6.71

The Hybrid CO_2 ACHP/EAHE cycle exhibited a 30% higher COP compared to R-410A and a remarkable 192% increase compared to the CO_2 transcritical cycle. This significant advantage underscores its potential in mitigating the indirect environmental impact of the cycle. Based on these findings, the Hybrid CO_2/EAHE system demonstrates promising results for the cooling season. However, heating presents a more intricate challenge due to limitations in condensing temperature. During the cooling season, evaporation and condensing temperatures were considered as -2°C and 45°C, respectively. For the Hybrid CO_2/EAHE cycle, the evaporation temperature remains constant, while the condensing temperature is lowered to 30°C. This adjustment also applies to the heating case. The table below outlines the evaporation and condensing temperatures for both cooling and heating scenarios.

Table 4. Cycle evaporation and condensing temperatures

Cycle Option	Evaporation Temperature (°C)	Condensing Temperature (°C)
Cooling		
R-410A	-2	45
CO_2 Transcritical	-2	45
Hybrid CO_2/EAHE	-2	28
Heating		
Cycle Option	**Evaporation Temperature (°C)**	**Condensing Temperature (°C)**
R-410A	0	28
CO_2 Transcritical	0	28
Hybrid CO_2/EAHE	7	28

CO_2 boasts numerous advantageous properties that render it well-suited for various refrigeration applications, including cascade cycles and low-temperature scenarios where the condensing process occurs at temperatures lower than its critical temperature of 30.98°C. One of the key physical advantages of CO_2 over other refrigerants is its low surface tension, a property that significantly influences the fluid's heat and mass transfer behaviour. As depicted in Fig. 14, the surface tension of CO_2 is approximately 50% of that of R-410A, providing a substantial benefit in applications requiring rapid phase change. Low surface tension facilitates the formation of smaller liquid droplets and promotes their uniform distribution over heat exchange surfaces. This characteristic enhances the initiation of the evaporation process by reducing the energy barrier for phase transition, allowing CO_2 to absorb heat more efficiently. In practical applications, this property translates to improved performance in low-temperature cooling systems, where efficient evaporation is crucial for maintaining system effectiveness. Furthermore, reduced surface tension contributes to a more stable film boiling regime and minimizes the risk of dry-out during heat exchange, which is particularly advantageous in CO_2 cycles operating under high pressure. This combination of rapid phase change and stable boiling dynamics underscores the suitability of CO_2 as a refrigerant in cutting-edge cooling technologies [29].

Furthermore, integrating an EAHE can significantly reduce the compression ratio and compressor power required for the CO_2 cycle. In the case of the R-410A cycle, the compression ratio was calculated at 2.49, with a higher side pressure reaching 2,671 kPa. Additionally, the compressor suction volume flow rate was determined to be 6.381 m^3/h, with a compressor discharge temperature of 74.8°C.

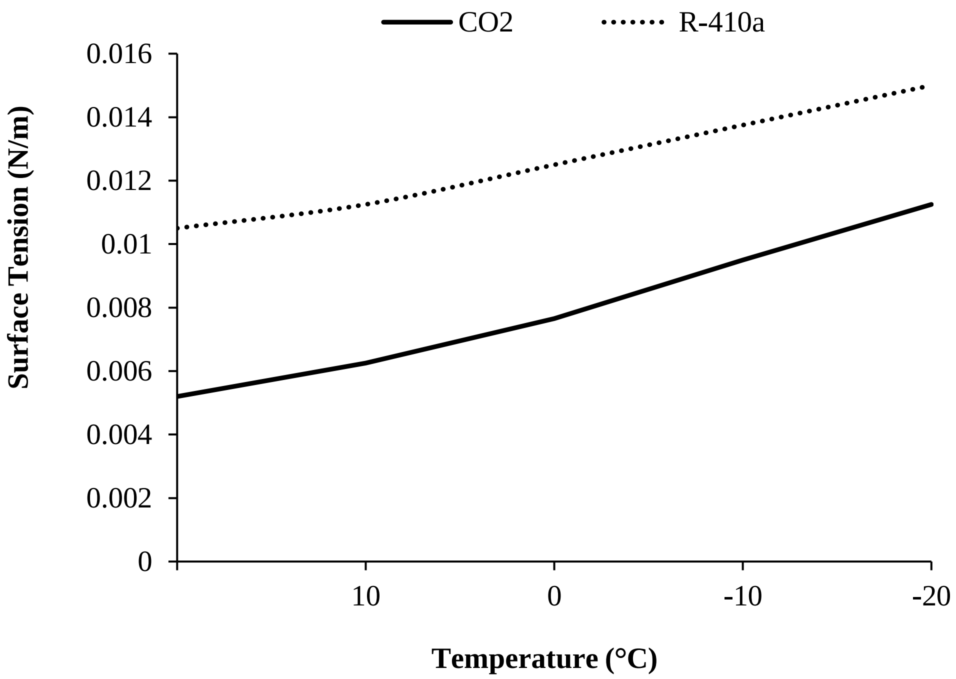

Figure 14. CO_2 refrigerant surface tension at different temperatures

Examining the schematics of the three cycles reveals a direct relationship between cycle COP and heat dissipation through the gas cooler in the transcritical cycle or the condenser in the conventional refrigeration cycle. As heat dissipation increases, the cycle COP decreases. This phenomenon can be attributed to the increased work required to elevate the CO_2 temperature to 45°C, which necessitates additional compression work and results in heat release in the gas cooler.

In any refrigeration cycle, the refrigerant temperature must surpass that of the surrounding environment (whether water, soil, or air) to enable thermal energy transfer to the environment through the condenser or gas cooler. Conversely, the refrigerant temperature must be sufficiently lowered to facilitate heat transfer from the conditioned space to the refrigerant in the evaporator. This temperature modulation is achieved by adjusting the refrigerant pressure and utilizing pressure-related evaporation and condensing temperatures. Consequently, the thermodynamic and thermophysical properties of the working fluid, along with the operating conditions of the application where the cycle is deployed, dictate the operating pressure of the cycle, thereby influencing the cycle Coefficient of Performance.

When the EAHE was employed to cool the CO_2 condenser, a separate energy and mass balance assessment was performed to ensure the accuracy of the coupled simulation. Since the EAHE operates on the air side, exchanging heat with the surrounding soil rather than the refrigerant directly, the balance was evaluated across the air domain and the ground interface. The mass balance confirmed that the air mass flow rate entering and leaving the EAHE remained constant within a deviation of less than 1%, indicating no significant air leakage or accumulation within the buried duct. This consistency validates the steady-state flow assumption used in the thermal modeling of the exchanger. The energy balance verified that the difference between the enthalpy of the incoming and outgoing air streams closely matched the rate of heat exchanged with the soil wall, with discrepancies below 3%. This confirms the thermodynamic consistency of the simulation and that the convective and conductive heat transfer mechanisms were properly captured.

Furthermore, the heat dissipation analysis revealed a maximum heat rejection of 18.2 kW through the EAHE-assisted condenser, which aligns with theoretical expectations since the total rejected heat equals the evaporator load plus the compressor’s work input. It is important to note that this represents the peak heat dissipation under full-load conditions. During most of the cooling season, when the air and soil temperatures are more moderate, the EAHE rejects less heat, which reduces compressor work and improves overall system efficiency.

However, it is also essential to recognize a limitation: for human comfort cooling applications, the reduction of EAHE outlet air temperature is constrained by the proximity of the desired room temperature to the critical temperature of CO_2 (30.89 °C). Excessive subcooling could reduce system stability or performance under transcritical conditions. Thus, while the EAHE significantly enhances heat rejection efficiency, its operation must be balanced with the thermodynamic requirements of the CO_2 cycle.

3.1 Energy Consumption and Environmental Impact Analysis

HVAC systems exert environmental impact both directly, through the global warming potential of refrigerant leakage, and indirectly, through energy consumption associated with CO_2 emissions from energy production processes. Hence, estimating the system's environmental impact over its lifespan is crucial. One effective method for this is through estimating the TEWI, which considers both direct and indirect environmental effects, as expressed in Eq. 29. As illustrated in Table 5, the Hybrid CO_2

ACHP/EAHE option demonstrated lower lifetime energy consumption and reduced environmental weighted impact compared to both the conventional R-410A system and the CO_2 transcritical cycle. Notably, while CO_2 exhibits lower direct impact than R-410A due to its lower Global Warming Potential, the CO_2 transcritical cycle exhibited higher total environmental impact due to its relatively lower COP and, consequently, higher energy consumption, leading to elevated direct environmental impact.

Table 5. Cycle Environmental Analysis

Cycle	SEER c	SEER h	GWP	LTEC (kWh)	TEWI
R-410A ACHP	14.44	13.78	2,088.00	197,839.32	154,758.30
CO_2 TRANS. ACHP	6.45	21.44	1.00	343,168.80	250,518.17
Hybrid CO_2/EAHE	18.82	24.91	1.00	138,451.57	101,074.60

The hybrid CO_2 ACHP/EAHE cycle demonstrated a 30% lower lifetime energy consumption compared to the R-410A cycle and a remarkable 59% reduction compared to the CO_2 transcritical cycle. Furthermore, it offered a 32% and 59% lower TEWI than the R-410A and CO_2 transcritical cycles, respectively. As depicted in Fig. 15, both the hybrid and transcritical cycle's environmental impact primarily stems from the indirect impact of energy consumption, which is significantly influenced by the carbon dioxide emission factor. This factor denotes the amount of carbon dioxide emitted for every kWh of energy produced, and its reduction can be achieved by increasing the proportion of renewable energy generation. With the anticipated growth of renewable energy generation in the future, TEWI for CO_2 cycles is expected to decrease even further.

Currently, the indirect impact of the cycle has a more pronounced influence on TEWI than the direct impact, even for refrigerants with relatively high GWP, such as R-410A. The direct impact of the R-410A cycle constituted only 8% of its TEWI, whereas it was nearly negligible for the CO_2 cycles. However, the percentage of the refrigerant's direct impact is projected to increase in the future, leading to a reduction in TEWI as more renewable energy resources are adopted on a national scale.

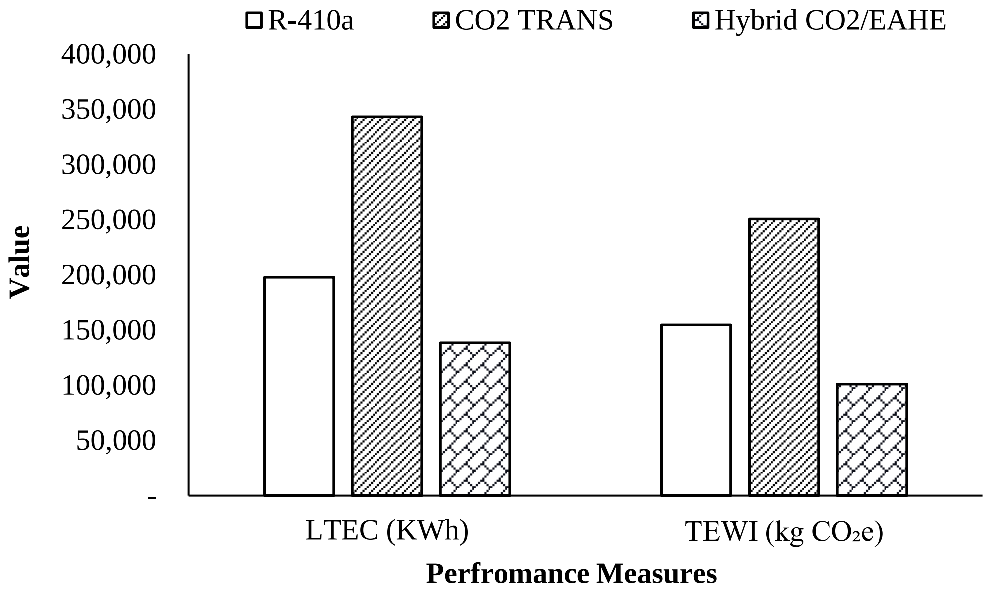

Figure 15. Cycle Energy and Environmental Performance

These findings underscore the potential of utilizing CO_2 as a refrigerant in building cooling applications. EAHEs emerge as simple yet robust heat exchangers capable of withstanding diverse weather conditions over extended periods without requiring maintenance. Integrating the building climate control system with EAHEs yields significant environmental benefits.

The air flow rate and velocity within the EAHE significantly influence the overall thermal and environmental performance of the CO_2 air-conditioning heat pump system. Increasing the air velocity enhances convective heat transfer between the air and the surrounding soil, improving the thermal exchange and stabilizing the inlet air temperature to the condenser. This leads to a smaller temperature difference across the refrigeration cycle, thereby reducing compressor work and improving the system's COP.

However, this improvement is not linear or indefinite. As the air velocity increases, the pressure losses along the EAHE ductwork become more pronounced, requiring additional fan power to maintain the desired air flow. Since fan energy consumption increases rapidly with air velocity, the net system efficiency may decline beyond a certain point. Therefore, an optimal air flow rate exists where the combined compressor and fan energy use is minimized, yielding the highest overall COP.

This trade-off also affects the TEWI. The indirect component of TEWI, driven by electrical energy consumption, dominates the total environmental footprint of the system. Thus, while moderate increases in air velocity can improve COP and reduce compressor energy use, excessive air speeds can increase total power consumption and offset the environmental benefits. Achieving an optimal balance between heat transfer enhancement and auxiliary energy use is therefore critical for minimizing TEWI.

An important limitation arises from the thermodynamic characteristics of CO_2 and the comfort cooling requirements. The critical temperature of CO_2 (30.89 °C) constrains the extent to which the EAHE outlet air temperature can be reduced. In human comfort cooling applications, indoor setpoint temperatures are typically around 24–26 °C, which is relatively close to the CO_2 critical point. Excessive subcooling of the EAHE outlet air provides little thermodynamic advantage and can even cause the system to operate inefficiently in transcritical mode if the condenser temperature approaches or exceeds the critical region. Consequently, while deeper burial and longer EAHE pipes can improve soil–air heat exchange, the resulting temperature reduction must remain within practical limits for comfort applications and CO_2 cycle stability.

Overall, the results indicate that moderate air velocities and optimized EAHE lengths and burial depths yield the best performance. These configurations achieve a favorable balance between compressor and fan power, maintain appropriate CO_2 condenser operating conditions near 30–31 °C, and minimize TEWI. This emphasizes the importance of integrating thermodynamic, environmental, and comfort constraints when optimizing EAHE-assisted CO_2 heat pump systems.

Furthermore, employing a control strategy enables direct utilization of the EAHE to cool or heat the space without activating the mechanical air conditioning system. This integration involves incorporating temperature sensors, humidity sensors, and motorized dampers. Such a system enhances environmental efficiency by utilizing the EAHE outlet air for cooling or heating purposes when temperature and humidity levels fall within acceptable ranges. This approach optimizes energy utilization and reduces reliance on traditional cooling and heating mechanisms, thereby further enhancing environmental sustainability.

3.2 EAHE Outlet Temperature Validation

Validating the outlet temperature of an EAHE is critical for ensuring the system's reliability and effectiveness. While subsoil temperature estimation involves some uncertainty due to variations in thermal properties and moisture content across locations, extensive research has shown that subsoil temperatures at depths of 2–4 m remain relatively stable year-round. These temperatures generally align with the annual mean ambient temperature. For instance, empirical data from Sydney indicates a subsoil temperature range of 18–19°C, which agrees with similar studies [30,31].

This consistency in subsoil temperature underscores the potential for leveraging the earth's thermal properties for energy savings. However, it is important to address potential changes in subsoil temperature caused by the EAHE's heat rejection. Although some studies suggest that this effect is negligible [32], it was not included in this analysis due to challenges in accurately estimating it and the minimal impact reported in the literature. To critically assess the results, the trend observed in the graph was compared with established research on EAHE systems. The temperature profile demonstrates a decline in outlet temperature as EAHE length increases, which is consistent with known thermodynamic principles and prior studies. Specifically, as air flows through the EAHE pipe, it exchanges heat with the surrounding soil, leading to a progressive temperature drop. The decline is initially steep and becomes less pronounced as the pipe length increases, reflecting the diminishing effectiveness of longer EAHE systems.

This behaviour is strongly supported by studies. Bisoniya (2015) noted that outlet temperatures stabilize beyond 40–50 meters, with diminishing cooling effects thereafter [33]. Kumar et al. (2016) observed optimal performance at pipe lengths of 30–40 meters, with minimal improvement beyond this range [34]. Similarly, Santamouris et al. (2018) reported a temperature drop of 3–6°C, predominantly in the first half of the pipe length [35]. In our results, the outlet temperature decreases sharply from 23°C to 19°C within the first 30 meters, followed by a gradual leveling off beyond 50 meters. This aligns closely with the asymptotic behaviour reported by prior studies, supporting the reliability of the findings. However, it is important to evaluate these comparisons critically. While the observed trends strongly correspond with the general behaviour described in the literature, slight variations in the exact lengths at which diminishing returns occur may arise from differences in soil thermal conductivity, air velocity, or site-specific conditions. For example, while Bisoniya (2015) identified stabilization at 40–50 meters, our results show a flattening around 50 meters. This suggests that while the overall trends are consistent, precise outcomes are sensitive to local factors [33]. Similarly, the steepest temperature drop observed in the first 30 meters matches the findings of Kumar et al. (2016) and Santamouris et al. (2018), though minor deviations in the magnitude of the temperature drop could reflect differences in soil and air properties across studies [34] [35]. Further validation could involve refining model inputs, such as soil thermal conductivity, air velocity, and the ambient air-to-ground temperature gradient, to improve alignment with site-specific conditions.

Table 6. Results Validation Against Published Studies

Study	Trends Observed in the Study	Comparison with the Present Study	Remarks
Bisoniya (2015) [33]	Outlet temperature stabilizes beyond 40–50 meters.	Flattening was observed around 50 meters.	Strong agreement, diminishing returns aligned.
Kumar et al. (2016) [34]	Optimal performance achieved at 30–40 meters.	Steepest declines between 10–30 meters; levels off after 40.	Matches performance reduction pattern.
Santamouris et al. (2018) [35]	3–6°C drop occurs mostly in the first half of the pipe.	Initial drop from ~23°C to 19°C observed within 30 meters.	Consistent with sharper early decrease.

3.3 Error Analysis

This section examines potential sources of error in the study, assessing their impact on the model's predictions of energy consumption, TEWI, and overall system performance. A thorough understanding of these uncertainties is essential for validating the results and ensuring the robustness of the proposed CO_2-based system integrated with an EAHE.

The mathematical model relies on simplifying assumptions, including constant subsoil temperatures, uniform soil properties, and steady-state operation. While these assumptions streamline the analysis, they may not fully capture real-world complexities. For example, variations in soil moisture content and thermal conductivity influence heat transfer rates, potentially affecting EAHE outlet temperatures and system efficiency. Sensitivity analysis showed that soil thermal conductivity variations could introduce up to a 10% error in heat transfer efficiency, while subsoil temperature fluctuations could cause a 5% deviation in EAHE outlet temperature. To mitigate these uncertainties, conservative assumptions were applied, incorporating annual subsoil temperature variations as shown in Fig. 4.

The EAHE design assumes uniform soil properties, such as thermal conductivity and specific heat. However, natural variations in soil composition, moisture content, and seasonal changes can alter heat transfer rates. The model also assumes idealized heat exchanger performance, neglecting potential inefficiencies like heat losses to the environment. Sensitivity analysis, considering ±5% variations in soil thermal conductivity, revealed a ±3% impact on predicted outlet temperatures and a ±2% effect on energy consumption. These findings highlight the importance of site-specific soil characterization to optimise EAHE performance. The model uses average climate data for Sydney, Australia, with subsoil temperatures ranging from 15.5°C to 20.1°C at a depth of 2.5 m. However, real-world conditions may differ due to climatic changes, seasonal fluctuations, and unexpected weather patterns. By varying air temperature by ±3°C and subsoil temperature by ±1°C, the analysis found that environmental variability could cause up to a 5% deviation in system performance. This emphasizes the need to account for long-term climatic trends in system design and operation. Comparisons between the proposed CO_2 ACHP/EAHE hybrid system, R-410A, and CO_2 transcritical cycles assume similar operating conditions. However, differences in system design and operating parameters could introduce errors in these comparisons. Sensitivity analysis on factors such as compressor efficiency, evaporator temperatures, and heat exchanger effectiveness revealed that comparative analysis errors could reach 10%. Standardized assumptions are therefore necessary to ensure reliable cross-system evaluations.

The results presented in Table 7 are consistent with the sensitivity analysis findings, demonstrating the strong dependence of the CO_2 system's performance on the EAHE outlet temperature under both cooling and heating modes. As soil temperature fluctuates throughout the year, the condenser inlet temperature also varies, directly influencing the system's COP. During the colder months, when the EAHE delivers air at approximately 16–17 °C to the evaporator, the CO_2 cycle operates in heating mode and achieves its highest efficiency, with COP values reaching up to 6.9. Conversely, during the warmer months, when the soil temperature rises toward 19–20 °C, the system operates in cooling mode, resulting in higher condenser inlet temperatures and a corresponding decrease in COP to around 4.4. This seasonal variation highlights the thermal sensitivity of the CO_2 system to the gas-cooler inlet temperature and confirms that even small reductions of 2–3 K can significantly enhance overall system performance. These findings reinforce the effectiveness of the EAHE as a pre-conditioning unit for CO_2-based systems, improving both heating and cooling efficiency through stable subsoil temperature utilization.

Table 7 The system COP monthly predictions

Month	Sub-Soil (°C)	Outdoor HX inlet (°C)	ΔT (K)	Estimated COP
Jan	17.9	20.9	19.1	4.52
Feb	18.7	21.7	18.3	4.45
Mar	19.2	22.2	17.8	4.40
Apr	19.4	22.4	17.6	4.39
May	19.1	22.1	17.9	4.41
Jun	18.5	21.5	18.5	4.46
Jul	17.7	20.7	19.3	6.71
Aug	17	20	20	6.80
Sep	16.4	19.4	20.6	6.87

Oct	16.2	19.2	20.8	6.90
Nov	16.4	19.4	20.6	6.87
Dec	17	20	20	4.59

In summary, while the proposed CO_2 ACHP/EAHE hybrid system's performance predictions are subject to uncertainties, primarily in thermodynamic property data, soil thermal conductivity, and environmental conditions, sensitivity analysis indicates that the overall impact on energy consumption and TEWI remains within ±5%. These findings affirm the robustness of the study and highlight the potential of the CO_2 ACHP/EAHE system as a sustainable solution for reducing energy consumption and environmental impact in air conditioning applications.

4. Potential Applications of the Hybrid CO_2 HP/EAHE System

The hybrid CO_2-ACHP/EAHE system represents an innovative and sustainable solution for enhancing energy efficiency and reducing environmental impact across various building applications. Its versatility makes it suitable for residential, commercial, and industrial contexts, though its feasibility and performance depend on factors such as space availability, climatic conditions, and system integration.

In residential settings, the hybrid system offers a sustainable alternative for heating and cooling, particularly in regions with moderate to high energy demands. The system ensures consistent and efficient operation year-round by leveraging stable subsoil temperatures through the EAHE. This makes it an attractive option for individual homes or multi-family housing complexes, providing the dual benefits of reduced energy consumption and lower greenhouse gas emissions. However, feasibility in residential applications largely depends on space availability for EAHE installation. Suburban or rural homes with larger plots are better suited for the required underground piping, while urban residences may face challenges due to limited land area. Innovative solutions, such as vertical EAHE systems or shared community-based installations, can address these constraints. Early integration during the design and construction phases is critical to optimize installation costs and ensure compatibility with other building systems. Commercial buildings, including offices, shopping centres, and hotels, stand to benefit significantly from the hybrid CO_2 HP/EAHE system. These spaces typically experience larger cooling loads and extended operating hours, making energy efficiency a top priority. The system's ability to reduce TEWI aligns well with the growing demand for green building certifications and compliance with stringent environmental regulations. However, deploying the system in commercial settings requires careful consideration of factors such as land availability for EAHE installation and the building's energy profile. Modular or shared EAHE systems can enhance adaptability for high-rise buildings or urban sites with limited outdoor space. Retrofitting existing commercial buildings may pose challenges, but creative solutions, such as utilizing common areas or parking spaces, can improve feasibility. Industrial facilities, such as manufacturing plants, warehouses, and food processing units, often have high energy demands and specific thermal requirements, making the hybrid system a promising option. Its ability to efficiently dissipate heat and maintain stable operating temperatures aligns well with industrial processes requiring consistent thermal regulation. The scalability of the EAHE design is particularly advantageous for larger sites with ample space for underground piping. While the upfront infrastructure investment may be higher than traditional HVAC systems, the long-term energy savings and environmental benefits can offset these costs. Additionally, the system supports corporate sustainability goals, especially in industries with high carbon footprints, where reducing emissions is both a regulatory and reputational priority. Further energy savings can be achieved by incorporating economizers and control options that allow direct use of external air when outdoor temperatures are suitable for thermal comfort.

The feasibility of integrating the hybrid CO_2-ACHP/EAHE system depends on meticulous planning and seamless integration. Early-stage design is crucial to optimize EAHE dimensions, site layout, and compatibility with existing systems, thereby reducing installation costs and minimizing disruptions. For existing buildings, retrofitting is possible but requires thorough site evaluations to address challenges such as space limitations and infrastructure compatibility. Environmental and climatic conditions also play a significant role in system performance. Locations with temperate climates, stable subsoil temperatures, and favourable soil properties are ideal for maximizing EAHE efficiency. In contrast, regions with extreme weather or variable soil types may require more complex designs, such as deeper or larger EAHE installations, to achieve comparable performance. Long-term system performance relies heavily on continuous maintenance. Factors such as soil compaction, pipe fouling, and changes in soil thermal properties must be monitored regularly to prevent performance degradation. A lifecycle approach to system design, implementation, and operation is essential to ensure sustained efficiency and reliability. By addressing these considerations and leveraging its unique benefits, the hybrid CO_2-ACHP/EAHE system has the potential to revolutionize heating and cooling across residential, commercial, and industrial sectors, aligning with global trends toward sustainable and energy-efficient technologies.

Handling CO_2 in its liquid state requires careful attention to its thermophysical properties to ensure safe and efficient operation. Liquid CO_2 is highly dense and undergoes significant thermal expansion with temperature variations, necessitating pressure-rated storage and piping systems. Cryogenic storage tanks equipped with pressure relief valves are commonly used to manage volume changes and prevent over-pressurization. Insulated piping is essential during transfer to minimize heat ingress and reduce the risk of vaporization. Material selection is critical, with stainless steel or compatible alloys preferred for their ability to withstand low temperatures and resist corrosion. Flow control devices, such as cryogenic pumps and precision valves, are necessary to regulate liquid CO_2 flow while maintaining stable pressures. Safety measures, including CO_2 sensors for leak detection and strict procedural controls during depressurization, are vital to mitigate risks associated with CO_2's rapid phase changes, particularly in confined spaces where oxygen displacement can occur. These measures ensure the safe and efficient utilization of CO_2 in refrigeration and heat exchange applications [36].

5. Conclusion

This study investigates the potential of integrating CO_2-ACHP systems EAHE to overcome some of the inherent challenges of CO_2 refrigeration, such as high cycle pressures and transcritical operation. While CO_2 transcritical cycles currently fall short of conventional refrigerant performance in certain aspects, this research demonstrates that CO_2 can still offer significant advantages in various applications, particularly in contexts where energy efficiency and environmental impact are prioritized.

The novel contribution of this study lies in the exploration of the hybrid CO_2 ACHP/EAHE system, which integrates the unique thermal characteristics of the EAHE with the CO_2 refrigeration cycle to reduce energy consumption and environmental impact. The key findings of this research include:

- The ability of EAHEs to stabilize air temperatures year-round, closely aligning with the mean annual temperature of the location, offering potential for passive temperature regulation.
- Subsoil temperatures in Sydney, Australia, are found to be between 15.5–20.1°C at a depth of 2.5 m, with a delay of approximately 75 days in response to air temperature changes.
- The EAHE outlet temperature achieved is approximately 19.25°C for a 35 m pipe length, suitable for cooling applications.

- The proposed CO_2 ACHP/EAHE hybrid system outperforms both R-410A and CO_2 transcritical cycles, with a 30% reduction in energy consumption and TEWI compared to R-410A, and a 59% reduction compared to the CO_2 transcritical cycle.
- While the system demonstrates significant energy savings and environmental benefits, the challenge of space constraints for EAHE installation remains, especially in existing buildings or retrofit projects. The system is most effective when incorporated in the early stages of project design, helping to reduce CAPEX through lower installation costs.

In conclusion, the CO_2 ACHP/EAHE hybrid system demonstrates strong potential for reducing the environmental footprint of heating and cooling applications across residential, commercial, and industrial sectors. The results highlight its capacity to achieve substantial energy savings and promote long-term sustainability, particularly when integrated with renewable energy sources. This research represents an important advancement in the broader adoption of CO_2 as a natural refrigerant and underscores the value of incorporating innovative subsystems such as the EAHE to enhance overall energy efficiency and minimize environmental impact.

6. Study limitations

The study faced several limitations that should be considered when interpreting the results and extrapolating findings to other contexts:

1. The mathematical model utilized in this study is based on idealized assumptions for calculating subsoil temperature and the EAHE outlet temperature. While these estimations provide valuable insights, they do not account for dynamic factors such as seasonal soil moisture variations, heterogeneous soil compositions, or localized changes in soil temperature around the EAHE pipes.
2. Due to the operational principles of the EAHE, the study was conducted for a specific temperate climate zone (Sydney, Australia) under the assumption of uniform soil properties. Although this provides relevant insights for similar climates, the results may not be directly transferable to regions with significantly different climatic conditions, such as arid or tropical zones, or soils with extreme properties. While these differences might not alter the findings, they could influence the required depth and length of the EAHE.
3. The model primarily addresses thermal performance, neglecting the potential impact of humidity levels on system efficiency. Air moisture content variations can influence heat transfer processes and overall cooling capacity, especially in humid climates. In this context, increased humidity would likely enhance heat transfer, positively affecting system performance.
4. Soil thermal diffusivity is treated as a static property derived from soil composition and moisture content. However, these properties are dynamic and can vary over time due to precipitation, evaporation, or other environmental factors. Such variability could affect the EAHE's thermal performance over its operational life.
5. Potential long-term changes in the EAHE system, such as pipe fouling, soil compaction or drying, or alterations in pipe material properties, were not considered in the study. These factors could influence the system's performance and efficiency over time.
6. The phase constant was determined using historical weather data, assuming a consistent lag in surface temperature for all years. This assumption may not account for anomalies caused by climate change or localized weather events, which could alter subsoil thermal profiles.
7. The hybrid system employing CO2 as a refrigerant was compared only with R-410A systems and the CO2 transcritical cycle. This narrow scope excludes other potentially viable refrigerants, such as R-32 or ammonia (R-717), which might offer competitive performance or efficiency benefits. These refrigerants were excluded due to their flammability or toxicity, narrowing the range of generalizable findings.

Addressing these limitations in future research could yield a more robust understanding of the integration of EAHE with CO2 heat pump systems, enhance system optimization, and expand applicability to diverse climates, soil conditions, and refrigerant technologies.

7. Future research directions

Based on the findings and conclusions of this research, several future directions can be suggested:

1. Long-Term Monitoring and Performance Evaluation: Conduct long-term monitoring studies to assess the performance of the CO_2 ACHP/EAHE Hybrid system in real-world applications. This would involve tracking energy consumption, system efficiency, and environmental impact over an extended period to validate the findings of this research and identify any potential areas for improvement.

2. Application in Different Climate Zones: Investigate the applicability of the CO_2 ACHP/EAHE Hybrid system in different climate zones and geographical regions. Understanding how the system performs in varying environmental conditions can help tailor its design and operation to maximize its effectiveness across diverse settings.

3. Lifecycle Analysis and Cost-Benefit Assessment: Conduct comprehensive lifecycle analyses and cost-benefit assessments to evaluate the long-term economic and environmental viability of implementing the CO_2 ACHP/EAHE Hybrid system. This would involve considering factors such as installation costs, maintenance requirements, energy savings, and environmental benefits over the system's lifespan.

4. Integration with Renewable Energy Sources: Investigate the integration of the CO_2 ACHP/EAHE Hybrid system with renewable energy sources such as solar or geothermal energy. By coupling the system with renewable energy generation, the overall environmental impact can be further reduced, and energy self-sufficiency can be enhanced.

5. Technological Advancements: Keep abreast of advancements in CO_2 refrigeration technology and earth-air heat exchange systems. Continued research and development in these areas may lead to the development of more efficient and cost-effective systems that further enhance energy savings and environmental sustainability.

6. Optimization of CO_2 ACHP/EAHE Hybrid System: Further research can focus on optimizing the design and operation of the CO_2 ACHP/EAHE Hybrid system to enhance its energy efficiency and environmental performance. This may involve exploring different system configurations, component sizes, and control strategies to maximize energy savings while minimizing environmental impact.

7. System Scalability: While this study concentrated on residential-scale applications of the EAHE-assisted CO_2 air conditioning and heat pump system, future investigations should extend toward commercial and industrial sectors, where larger thermal capacities and more dynamic load profiles are encountered. The integration of EAHEs in such large-scale systems may introduce additional technical challenges, including maintaining stable gas cooler and evaporator operating conditions, mitigating pressure losses along extended duct networks, and managing airflow resistance at elevated velocities. Addressing these factors will be essential to ensure consistent system performance and to preserve the energy and environmental advantages observed in smaller-scale installations. Furthermore, future studies could explore advanced control algorithms, hybrid operation modes, and the coupling of EAHEs with thermal energy storage to enhance system adaptability and optimize year-round efficiency under varying climatic and operational conditions.

By pursuing these future directions, researchers and practitioners can further advance the development and adoption of CO_2-based air conditioning systems integrated with earth-air heat exchange technology, contributing to sustainable building practices and mitigating the environmental impact of HVAC systems.

Declaration of competing interest: The authors of this work declare that they have no known competing interests or personal relationships that may have driven the results of the work reported in this paper.

Data Availability Statement: Data will be available upon reasonable request.

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