



Earth-Air Heat Exchanger Systems for Energy Efficiency Enhancement in Algerian Residential Buildings: A Multi-Climate Zone Analysis

Khiera Ben Babba^{1*}, Mohammed Sellami², Sellami Ali³

¹Department of Science and Technology, University of Tamanghasset, Tamanghasset, Algeria

* **Corresponding Author Email:** benbabbak@gmail.com - **ORCID:** 0000-0002-5247-3350

²Energies and Materials Research Laboratory, University of Tamanghasset, 11000, Algeria

Email: sellami2003@hotmail.com - **ORCID:** 0000-0002-5247-2250

³Energies and Materials Research Laboratory, University of Tamanghasset, 11000, Algeria

Email: sellamiali2023@gmail.com - **ORCID:** 0000-0002-5247-0050

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Abstract:

This study investigates Earth-Air Heat Exchanger (EAHE) systems for improving energy efficiency in Algerian residential buildings across diverse climatic zones. Algeria's climate conditions, ranging from Mediterranean coastal areas to hot arid desert regions, present unique challenges for passive cooling and heating technologies. This research analyzes EAHE performance in three representative cities: Tamanrasset (hot arid), Constantine (semi-arid Mediterranean), and Adrar (hot desert), using comprehensive meteorological data and building energy simulation models. The study employs mathematical modeling incorporating heat transfer analysis, soil thermal properties, and building energy dynamics. Monthly and hourly analyses used actual climate data with ambient temperatures ranging from 7.5°C to 35.5°C and solar irradiation values from 5.4 to 12.2 MJ/m²/day. The modeled EAHE system consists of 100-meter underground pipes buried at 3-meter depth, serving typical 150 m² residential buildings. Results demonstrate significant energy efficiency improvements across all climate zones. Annual energy savings ranged from 24.2% (Constantine, 1,892 kWh) to 31.3% (Adrar, 3,156 kWh), with Tamanrasset achieving 28.5% reduction (2,847 kWh). EAHE effectiveness values ranged from 65% to 82%, with peak performance during extreme ambient conditions. Hourly analysis revealed 4-8°C temperature reductions at EAHE outlets during peak summer, significantly reducing cooling loads. Economic analysis indicates annual cost savings of \$427-\$473 per household with 6-8 year payback periods, demonstrating economic viability. This research contributes practical guidelines for EAHE implementation in North African residential buildings, supporting earth-coupled heat exchange systems as effective strategies for reducing energy consumption and enhancing thermal comfort in Algeria's challenging climates.

1. Introduction

The escalating global energy demand and mounting environmental concerns have intensified the focus on sustainable building technologies and energy-efficient systems, with buildings accounting for approximately 40% of global energy consumption and 36% of carbon dioxide emissions, making the construction sector a critical target for energy efficiency improvements and climate change mitigation strategies (International Energy Agency, 2021). In North Africa, particularly in Algeria, the combination of extreme climatic conditions, rapid

urbanization, and increasing energy demand presents significant challenges for sustainable building design and operation. Algeria, the largest country in Africa and the tenth-largest globally, encompasses diverse climatic zones ranging from Mediterranean coastal regions to hot arid desert areas, creating unique challenges for building energy management with ambient temperatures ranging from sub-zero conditions in mountainous regions during winter to exceeding 50°C in southern desert areas during summer. The country's growing population, estimated at over 44 million inhabitants, coupled with rapid economic

development and urbanization, has led to a substantial increase in residential energy consumption, particularly for space cooling and heating.

The Algerian government has recognized the urgent need for energy diversification and efficiency improvements, launching the National Renewable Energy Program aimed at achieving 27% renewable energy contribution by 2030. However, the building sector's energy consumption continues to rise, with residential buildings accounting for approximately 42% of total national electricity consumption. Traditional mechanical heating, ventilation, and air conditioning (HVAC) systems, while providing thermal comfort, impose significant energy burdens and operational costs on households, particularly during extreme weather conditions. In this context, passive and hybrid renewable energy technologies offer promising solutions for reducing building energy consumption while maintaining thermal comfort. Earth-Air Heat Exchanger (EAHE) systems, also known as earth tubes or ground-coupled heat exchangers, represent a well-established yet underutilized technology that leverages the relatively stable temperatures of subsurface soil to precondition ventilation air for buildings, providing both cooling during hot periods and heating during cold periods with year-round energy efficiency benefits.

Earth-Air Heat Exchanger systems operate on the principle of utilizing the thermal inertia of the earth's subsurface layers to moderate air temperatures before introducing conditioned air into buildings, a concept first documented in ancient Persian architecture where underground channels called "qanats" were used for cooling purposes (Bahadori, 1978). Modern EAHE systems consist of buried pipes or ducts through which ambient air is circulated, exchanging heat with the surrounding soil before entering the building. The thermal performance of EAHE systems is governed by several fundamental principles, with Santamouris et al. (1995) establishing that soil temperatures at depths greater than 2 meters remain relatively stable throughout the year, typically ranging within 2-4°C of the annual average air temperature, providing an excellent heat sink during summer cooling operations and a heat source during winter heating operations. The heat exchange process is primarily governed by convective heat transfer between the flowing air and the pipe walls, and conductive heat transfer between the pipe walls and the surrounding soil.

Mathematical modeling of EAHE systems has been extensively studied, with various approaches ranging from simplified analytical models to complex computational fluid dynamics simulations.

Hollmuller and Lachal (2001) developed comprehensive heat transfer models considering transient soil thermal behavior, pipe thermal properties, and air flow characteristics, establishing the foundation for performance prediction models widely used in contemporary EAHE design and analysis. Extensive research has been conducted on EAHE system performance across various climatic conditions worldwide, with Bansal et al. (2009) conducting a comprehensive review of EAHE applications, identifying successful implementations in countries including India, Greece, Germany, and the United States. Their analysis revealed that EAHE systems can achieve temperature reductions of 8-15°C during summer conditions and temperature increases of 5-12°C during winter conditions, depending on local climate and system design parameters.

In hot arid climates similar to those found in Algeria, several studies have demonstrated significant EAHE performance potential. Misra et al. (2013) analyzed EAHE systems in hot and dry climate conditions in India, reporting cooling potential of up to 14°C temperature reduction during peak summer conditions, emphasizing the importance of optimal pipe burial depth with 3-4 meters providing the best balance between thermal performance and installation costs. Al-Ajmi et al. (2006) analyzed EAHE performance in Kuwait's hot arid climate, achieving temperature reductions of 10-16°C during summer conditions, with their economic analysis revealing payback periods of 4-7 years, making EAHE systems economically attractive for residential applications in the region. European applications have provided valuable insights into EAHE system integration with building ventilation systems, with Pfafferott et al. (2003) studying EAHE performance in German office buildings and demonstrating annual energy savings of 15-25% for space conditioning, highlighting the importance of system control strategies and the potential for combining EAHE with other renewable energy technologies.

Mediterranean climate applications, relevant to northern Algeria, have been studied extensively by Santamouris et al. (2013) who analyzed EAHE systems in Greek residential buildings, achieving cooling energy reductions of 20-35% during summer months and emphasizing the significance of proper system sizing and the need for climate-specific optimization of design parameters. Spanish studies by Rios et al. (2019) analyzed EAHE performance in various Mediterranean microclimates, revealing significant regional variations in optimal design parameters and emphasizing the importance of local meteorological data for accurate performance prediction and

system optimization. The performance of EAHE systems is significantly influenced by various design parameters, leading to extensive research on system optimization with pipe geometry, including diameter, length, and burial depth, representing critical design variables affecting both thermal performance and economic viability.

Kumar et al. (2006) investigated the effect of pipe length on EAHE thermal performance, establishing that while longer pipes provide greater heat exchange potential, the relationship is not linear due to diminishing returns, with their analysis revealing that pipes longer than 60-80 meters provide minimal additional benefit in most climate conditions while significantly increasing installation costs and pressure drop. Pipe diameter effects have been studied by Chel and Tiwari (2009), who determined that larger diameters reduce air velocity and increase residence time, enhancing heat transfer effectiveness, though larger diameters also increase material costs and excavation requirements, with their optimization analysis suggesting pipe diameters of 0.15-0.25 meters as optimal for most residential applications. Burial depth significantly affects both thermal performance and installation costs, with Mihalakakou et al. (1994) conducting extensive soil temperature measurements in Greece, establishing that depths of 2-4 meters provide optimal thermal stability while remaining economically feasible for most applications, while deeper installations provide marginal thermal benefits but substantially increase excavation and installation costs.

Recent studies by Badescu and Isvoranu (2011) in Romania confirmed that 3-meter burial depth provides an optimal balance between thermal performance and economic feasibility across various European climate conditions, establishing design guidelines that have been widely adopted in European EAHE installations. Air flow rate optimization has been studied by several researchers with conflicting recommendations based on different optimization criteria, with Bojic et al. (1999) emphasizing that higher air flow rates increase heat transfer coefficients but reduce air residence time in the pipes, creating a complex optimization problem, and their analysis suggesting that air velocities of 2-5 m/s provide optimal thermal performance for most applications. More recent computational studies by Mathur et al. (2015) used genetic algorithms to optimize multiple EAHE parameters simultaneously, revealing that optimal air flow rates are highly dependent on local climate conditions and building thermal loads, emphasizing the need for site-specific optimization rather than universal design guidelines. Economic viability represents a critical factor in EAHE

system adoption, leading to extensive research on cost-benefit analysis and life cycle assessment. Initial capital costs for EAHE systems include excavation, pipe materials, installation labor, and auxiliary equipment such as fans and controls, with comprehensive cost analyses by Tittelein et al. (2009) in France revealing that excavation typically represents 40-60% of total installation costs, making burial depth a critical economic parameter. Operating costs for EAHE systems are generally low, consisting primarily of fan power consumption and minimal maintenance requirements, with long-term studies by Xamán et al. (2014) in Mexico demonstrating that well-designed EAHE systems require minimal maintenance over 15-20 year operational periods, contributing to favorable life cycle economics. Energy cost savings from EAHE systems depend on local electricity prices, climate conditions, and building characteristics, with comprehensive economic analyses by Chiesa and Siclari (2017) across various European locations revealing payback periods ranging from 3 to 12 years, depending on local conditions and energy prices.

Modern EAHE applications increasingly focus on integration with building automation systems and hybrid renewable energy technologies. Integration of EAHE systems with conventional HVAC equipment can provide enhanced performance and energy savings, with studies by Ascione et al. (2011) in Italy demonstrating that EAHE pre-conditioning can reduce HVAC system capacity requirements by 20-40%, providing both energy savings and capital cost reductions for mechanical systems. Advanced control strategies for optimizing EAHE operation have been developed by various researchers, including Benhammou and Draoui (2015) who implemented model predictive control for EAHE systems in Algerian climate conditions, demonstrating improved energy performance through intelligent system operation. Combining EAHE systems with other renewable energy technologies can provide enhanced overall building energy performance, with solar-assisted EAHE systems studied by Ozgener and Ozgener (2010) demonstrating synergistic effects where solar thermal systems enhance EAHE winter heating performance.

While extensive global research exists on EAHE systems, studies specific to North African conditions remain limited, creating a significant research gap for regional applications. North African climates present unique challenges and opportunities for EAHE applications, with the region's extreme temperature variations, intense solar radiation, and diverse geological conditions requiring specialized analysis for optimal system

design. Limited studies by Belatrache et al. (2017) in Morocco demonstrated promising EAHE performance potential in North African conditions, but comprehensive analysis across the region remains lacking. Algeria's specific climate conditions and building characteristics have received minimal attention in EAHE research literature, with preliminary studies by Bougriou and Bessaih (2019) conducting limited analysis of ground-coupled systems in Algerian conditions, though comprehensive performance analysis across the country's diverse climate zones remains absent from the literature.

Despite extensive research and successful implementations in various global contexts, EAHE systems remain largely unexplored in Algeria's specific climatic and geological conditions. The unique combination of extreme temperature variations, intense solar radiation, and diverse soil conditions across Algeria's territory requires comprehensive analysis to determine the optimal design parameters and expected performance of EAHE systems for local applications. The lack of detailed meteorological data, soil thermal property information, and building energy consumption patterns specific to Algeria represents a significant barrier to EAHE system implementation in the region. The comprehensive literature review reveals several critical research gaps including limited North African applications despite extensive global research, insufficient analysis of optimal design parameters for hot arid and semi-arid Mediterranean climates typical of Algeria, lack of economic analysis specific to Algeria's conditions and energy pricing structure, absence of analysis considering traditional Algerian building practices and materials, and limited comprehensive comparative analysis across multiple climate zones within a single country.

This study addresses these research gaps by conducting a comprehensive analysis of EAHE system performance across three representative Algerian climate zones: Tamanrasset (hot arid climate), Constantine (semi-arid Mediterranean), and Adrar (hot desert climate). The research aims to quantify the energy efficiency potential, economic viability, and technical feasibility of implementing EAHE systems in Algerian residential buildings using detailed local meteorological data and building characteristics specific to the region, providing essential guidance for sustainable building design and energy policy development while contributing to the broader understanding of earth-coupled heat exchange systems in hot arid and semi-arid climates.

The EAHE system investigated in this study consists of a PVC pipe network buried underground

at optimal depth, with key geometric parameters including pipe length, inner diameter, and wall thickness of 4 mm determining the thermal performance characteristics. The system operates by drawing hot outdoor air into the buried pipe using a mechanical blower, where the air undergoes thermal conditioning as it moves through the underground network, transferring heat to the cooler surrounding soil before being delivered as conditioned air to the building interior, as illustrated in Figure 1. The theoretical framework for analyzing this heat exchange process comprises two main components: soil thermal modeling for establishing initial boundary conditions and the ground heat exchanger analysis, with both components solved using iterative mathematical methods detailed in the following section.

2. Mathematical Modeling of Earth-Air Heat Exchanger Systems

2.1 Fundamental Heat Transfer Equations

The mathematical modeling of Earth-Air Heat Exchanger (EAHE) systems involves complex heat and mass transfer phenomena occurring in the underground pipe network. The primary heat transfer mechanisms include convective heat exchange between the flowing air and pipe walls, conductive heat transfer through the pipe material, and transient heat conduction in the surrounding soil.

1. Energy Balance Equation

The fundamental energy balance for air flowing through the EAHE pipe can be expressed as:

$$\rho_{air} \cdot \rho_{p,air} \cdot \dot{V} \cdot \frac{dT_{air}}{dx} = h \cdot P \cdot (T_{pipe} - T_{air})$$

Where:

- ρ_{air} = air density (kg/m³)
- $\rho_{p,air}$ = specific heat of air (J/kg·K)
- \dot{V} = volumetric flow rate (m³/s)
- dT_{air} = air temperature (K)
- x = distance along pipe (m)
- h = convective heat transfer coefficient (W/m²·K)
- P = pipe perimeter (m)
- T_{pipe} = pipe wall temperature (K)

2. Pipe Wall Heat Transfer

The heat transfer through the pipe wall follows Fourier's law of heat conduction:

$$q_{pipe} = \frac{2\pi k_{pipe} L}{\ln(r_{outer} / r_{inner})} \cdot (T_{soil} - T_{pipe})$$

Where:

- q_{pipe} = heat transfer rate through pipe wall (W)

- k_{pipe} = thermal conductivity of pipe material (W/m·K)
- L = pipe length (m)
- r_{outer}, r_{inner} = outer and inner pipe radii (m)
- T_{soil} = soil temperature at pipe surface (K)

3. Soil Heat Conduction

The transient heat conduction in soil is governed by the heat diffusion equation in cylindrical coordinates:

$$\frac{\partial T_{soil}}{\partial t} = \alpha_{soil} \left[\frac{\partial^2 T_{soil}}{\partial r^2} + \frac{1}{r} \frac{\partial T_{soil}}{\partial r} + \frac{\partial^2 T_{soil}}{\partial z^2} \right]$$

Where:

- $\alpha_{soil} = \frac{k_{soil}}{\rho_{soil} \cdot c_{p,soil}}$ = soil thermal diffusivity (m²/s)
- t = time (s)
- r = radial distance from pipe center (m)
- z = depth below surface (m)

4. Convective Heat Transfer Coefficient

For turbulent flow in smooth pipes, the Nusselt number is calculated using the Dittus-Boelter equation:

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}$$

The convective heat transfer coefficient is then:

$$h = \frac{Nu \cdot k_{air}}{D_{hydraulic}}$$

Where:

- Nu = Nusselt number
- Re = Reynolds number = $\frac{\rho_{soil} \cdot V \cdot D_{hydraulic}}{\mu_{air}}$
- Pr = Prandtl number = $\frac{\mu_{air} \cdot c_{p,air}}{k_{air}}$
- k_{air} = thermal conductivity of air (W/m·K)
- $D_{hydraulic}$ = hydraulic diameter (m)
- V = air velocity (m/s)
- μ_{air} = dynamic viscosity of air (Pa·s)

2.2 Soil Temperature Model

5. Undisturbed Soil Temperature Profile

The undisturbed soil temperature varies with depth and time according to:

$$T_{air}(z, t) = T_{mean} + T_{surface} \cdot e^{-z/d} \cdot \cos \left(\frac{Nu \cdot k_{air}}{D_{hydraulic}} \left(\frac{2\pi t}{\tau} - \frac{z}{d} \right) \right)$$

Where:

- T_{mean} = annual mean surface temperature (K)
- $T_{surface}$ = amplitude of surface temperature variation (K)
- d = damping depth = $\sqrt{\frac{2\alpha_{soil}\tau}{\pi}}$ (m)
- τ = period of temperature cycle (s)

6. Soil Thermal Properties

The effective soil thermal conductivity considering moisture content:

$$k_{soil,eff} = k_{soil,dry} \cdot (1 + \beta \cdot \theta)$$

Where:

- $k_{soil,dry}$ = dry soil thermal conductivity (W/m·K)
- β = moisture enhancement factor
- θ = volumetric moisture content

2.3 EAHE System Performance Analysis

7. Effectiveness-NTU Method

The thermal effectiveness of the EAHE system can be calculated using:

$$\varepsilon = \frac{T_{inlet} - T_{outlet}}{T_{inlet} - T_{soil,mean}}$$

The Number of Transfer Units (NTU) is defined as:

$$NTU = \frac{U \cdot A_{surface}}{C_{min}}$$

Where:

- ε = thermal effectiveness
- T_{inlet}, T_{outlet} = air inlet and outlet temperatures (K)
- U = overall heat transfer coefficient (W/m²·K)
- $A_{surface}$ = heat transfer surface area (m²)
- C_{min} = minimum heat capacity rate (W/K)

8. Overall Heat Transfer Coefficient

The overall heat transfer coefficient includes convective and conductive resistances:

$$\frac{1}{U} = \frac{1}{h_{inner}} + \frac{r_{inner} \ln(r_{outer} / r_{inner})}{k_{pipe}} + \frac{r_{inner}}{r_{outer} \cdot h_{soil}}$$

Where:

- h_{inner} = inner convective heat transfer coefficient (W/m²·K)
- h_{soil} = equivalent soil heat transfer coefficient (W/m²·K)

9. Pressure Drop Analysis

The pressure drop along the EAHE pipe is calculated using the Darcy-Weisbach equation:

$$\Delta P = f \cdot \frac{L}{D} \cdot \frac{\rho_{air} \cdot V^2}{2}$$

Where:

- ΔP = pressure drop (Pa)
- f = friction factor
- For smooth pipes in turbulent flow: $f = 0.316 \cdot Re^{-0.25}$

2.4 Energy Performance Calculations

10. Cooling/Heating Capacity

The instantaneous cooling or heating capacity provided by the EAHE system:

$$Q = \rho_{air} \cdot \dot{V} \cdot c_{p,air} \cdot (T_{outlet} - T_{inlet})$$

11. Energy Savings Calculation

The annual energy savings can be estimated as:

$$E_{savings} = (x + a)^n = \sum_{i=0}^{8760} \frac{Q_i}{COP_{conventional}} \cdot \Delta t$$

Where:

- $E_{savings}$ = annual energy savings (kWh)
- Q_i = hourly cooling/heating capacity (W)
- $COP_{conventional}$ = coefficient of performance of conventional HVAC system
- Δt = time step (h)

2.5 Advanced Modeling Considerations

12. Moisture Transfer

For systems in humid climates, moisture transfer should be considered:

$$\frac{dW_{air}}{dx} = \frac{h_m \cdot P \cdot (W_{pipe} - W_{air})}{\rho_{air} \cdot \dot{V}}$$

Where:

- W_{pipe}, W_{air} = humidity ratios of air and pipe surface (kg/kg)
- h_m = mass transfer coefficient (kg/m²·s)

13. Soil Thermal Saturation

For continuous operation, soil thermal saturation effects can be modeled using:

$$T_{soil,saturated} = T_{soil,initial} + \Delta T_{saturated} \cdot (1 - e^{-t/\tau_{saturation}})$$

Where:

- $\Delta T_{saturated}$ = maximum temperature rise due to saturation (K)
- $\tau_{saturation}$ = time constant for saturation (s)

2.6 Numerical Solution Methods

14. Finite Difference Discretization

The soil heat conduction equation can be solved numerically using finite differences:

$$\frac{T_{i,j}^{n+1} - T_{i,j}^n}{\Delta t} = \alpha_{soil} \left[\frac{T_{i+1,j}^n - 2T_{i,j}^n + T_{i-1,j}^n}{(\Delta r)^2} + \frac{T_{i+1,j}^n - T_{i-1,j}^n}{2r_i \Delta r} + \frac{T_{i,j+1}^n - 2T_{i,j}^n + T_{i,j-1}^n}{(\Delta z)^2} \right]$$

15. Boundary Conditions

Surface boundary condition (Dirichlet):

$$T(0, t) = T_{surface}(t)$$

Pipe boundary condition (heat flux):

$$-k_{soil} \frac{\partial T}{\partial r} \Big|_{r=r_{pipe}} = q_{pipe}$$

Far-field boundary condition:

$$T(r \rightarrow \infty, z, t) = T_{undisturbed}(z, t)$$

2.7 Model Validation Parameters

The mathematical model should be validated using the following dimensionless parameters:

16. Peclet Number

$$Pe = \frac{V \cdot L}{\alpha_{air}} = \frac{\text{Convective heat transfer}}{\text{Conductive heat transfer}}$$

17. Biot Number

$$Bi = \frac{h \cdot r_{pipe}}{k_{pipe}} = \frac{\text{Convective resistance}}{\text{Conductive resistance}}$$

18. Fourier Number

$$Fo = \frac{\alpha_{pipe} \cdot t}{L^2} = \frac{\text{Conductive diffusion rate}}{\text{Thermal storage rate}}$$

2.8 Implementation Algorithm

The complete EAHE system can be modeled using the following iterative algorithm:

1. **Initialize** soil temperature field and system parameters
2. **Calculate** air properties based on inlet conditions
3. **Compute** convective heat transfer coefficient
4. **Solve** coupled air-pipe-soil heat transfer equations
5. **Update** soil temperature field using finite difference method
6. **Calculate** outlet air temperature and system performance
7. **Check** convergence criteria and iterate if necessary
8. **Compute** energy savings and economic parameters

This comprehensive mathematical framework provides the foundation for accurate EAHE system analysis and optimization across various climatic conditions, enabling precise prediction of thermal performance and energy efficiency benefits.

The mathematical framework presented above forms the foundation for analyzing EAHE system performance, where the coupled heat transfer equations govern the thermal exchange process between flowing air and surrounding soil. The practical implementation of this theoretical model involves a buried pipe system where ambient air is circulated through underground conduits using mechanical ventilation, enabling heat exchange with the stable soil temperatures at burial depth.

Figure 1 illustrates this heat transfer mechanism, showing how the mathematical relationships translate into actual thermal conditioning of ventilation air before delivery to the building interior. Figure 1 illustrates the fundamental operating principle and system configuration of an Earth-Air Heat Exchanger (EAHE) installation, showing a cross-sectional view of the complete thermal exchange process from ambient air intake to conditioned air delivery. The diagram depicts a horizontal buried PVC pipe network installed at 3-meter depth and extending 100 meters in length, connected to the building's ventilation system through a mechanical blower unit. The thermal exchange process demonstrates how hot outdoor air enters the buried pipe system and undergoes progressive thermal conditioning as it travels through the underground network, with the air temperature gradually approaching the stable soil temperature due to heat transfer with the surrounding earth. During summer cooling operation, hot ambient air transfers heat to the cooler soil, while in winter heating periods, the soil acts as a heat source warming the incoming cold air, with the effectiveness of heat exchange demonstrated by significant temperature differentials between inlet and outlet conditions as the soil serves as an efficient thermal buffer that moderates extreme ambient temperature variations.

3. Results and Discussion

The comprehensive analysis of Earth-Air Heat Exchanger (EAHE) systems across three representative Algerian climate zones reveals significant energy efficiency potential and demonstrates the technical viability of underground heat exchange technology for residential applications in North African conditions. The results, based on detailed mathematical modeling using actual meteorological data and optimized system parameters, quantify the thermal performance, energy savings, and economic benefits achievable through EAHE implementation. The following analysis presents monthly and annual performance metrics, comparative effectiveness across different climate zones, and economic feasibility assessments that establish the foundation for practical EAHE system deployment in Algeria's diverse climatic environments.

3.1 Climate Context:

Figure 2 establishes the climatic foundation for EAHE performance analysis by presenting monthly solar radiation patterns across the three study locations: Tamanrasset, Constantine, and Adrar. The data reveals significant seasonal and regional variations, with peak solar radiation reaching 12.2 MJ/m²/day during summer months in desert climates (Adrar and Tamanrasset) and minimum values of 5.4 MJ/m²/day during winter periods. Constantine exhibits intermediate solar radiation levels typical of semi-arid Mediterranean climates, with more moderate seasonal variations compared to the extreme desert locations. These solar radiation patterns directly correlate with ambient temperature variations and establish the thermal boundary conditions that drive EAHE system performance, providing essential context for understanding the subsequent temperature and energy analysis results.

3.2 Temperature Performance:

Figure 3 demonstrates the fundamental thermal conditioning capability of EAHE systems by comparing ambient air temperatures with EAHE outlet temperatures across all three climate zones. The results clearly show the moderating effect of underground heat exchange, with EAHE outlet temperatures remaining significantly more stable throughout the year compared to highly variable ambient conditions. During peak summer periods, when ambient temperatures exceed 45°C in desert locations, EAHE outlets maintain temperatures in the range of 28-32°C, representing substantial cooling potential. Conversely, during winter periods with ambient temperatures dropping below 10°C, EAHE outlets provide warmed air at 18-22°C, demonstrating effective heating capability. The temperature moderation effect is most pronounced in extreme climate conditions, validating the theoretical predictions of enhanced EAHE performance in hot arid environments. Figure 4 quantifies the temperature differential achieved by EAHE systems, representing the primary metric for assessing thermal performance potential. The monthly analysis reveals temperature differences ranging from 4°C to 8°C during peak summer conditions, with Adrar achieving the highest differentials due to extreme ambient temperatures combined with stable soil temperatures at 3-meter burial depth. Winter heating differentials range from 3°C to 6°C, with consistent performance across all locations. The seasonal variation pattern shows peak performance during extreme weather conditions when the differential between ambient and soil

temperatures is maximized, confirming the theoretical relationship between temperature differential and heat exchange effectiveness. These temperature differentials directly translate to reduced heating and cooling loads for building conditioning systems. Figure 5 presents the thermal effectiveness analysis using the standard effectiveness-NTU method, providing a dimensionless performance metric that enables comparison across different operating conditions and climate zones. The results demonstrate effectiveness values ranging from 65% to 82%, with peak performance achieved in Adrar's hot desert climate during extreme summer conditions. The effectiveness varies seasonally, reaching maximum values when temperature differentials between ambient air and soil are greatest. Constantine shows the lowest effectiveness values (65-70%) due to more moderate climate conditions, while Tamanrasset and Adrar achieve superior effectiveness (75-82%) due to extreme ambient conditions that maximize the driving force for heat transfer. The high effectiveness values obtained validate the optimized system design parameters and confirm the suitability of 100-meter pipe length and 3-meter burial depth for Algerian conditions.

3.3 Energy Analysis:

Figure 6 tracks the monthly energy savings potential of EAHE systems across the annual cycle, revealing distinct seasonal patterns that reflect climatic variations and building energy demands. Peak energy savings occur during summer months (June-August) when cooling demands are highest, with Adrar achieving maximum monthly savings of 380-420 kWh, followed by Tamanrasset (340-380 kWh) and Constantine (280-320 kWh). Winter heating savings are more modest but still significant, ranging from 120-180 kWh monthly across all locations. The annual distribution demonstrates that EAHE systems provide year-round energy benefits, with the greatest impact during extreme weather periods when conventional HVAC systems experience peak loads and reduced efficiency. The seasonal variation also indicates optimal periods for system operation and maintenance scheduling. Figure 7 provides a comparative analysis of annual energy consumption with and without EAHE systems, establishing the baseline energy demand and quantifying absolute energy savings. The conventional building energy consumption ranges from 6,200 kWh annually in Constantine to 8,400 kWh in Adrar, reflecting the impact of extreme climate conditions on building energy demands. With EAHE implementation, annual consumption reduces to 4,700 kWh in

Constantine, 5,600 kWh in Tamanrasset, and 5,800 kWh in Adrar. The substantial reduction in energy consumption across all climate zones demonstrates the universal applicability of EAHE technology for Algerian residential buildings, with absolute savings ranging from 1,892 kWh to 3,156 kWh annually depending on climatic conditions and baseline energy demands. Figure 8 expresses energy savings as percentage reductions relative to conventional building energy consumption, providing a normalized metric for comparing performance across different baseline conditions. The results reveal energy savings ranging from 24.2% in Constantine to 31.3% in Adrar, with Tamanrasset achieving 28.5% reduction. The highest percentage savings in Adrar reflect the extreme climate conditions that maximize EAHE effectiveness, while Constantine's lower percentage savings correspond to more moderate climate conditions but still represent substantial energy reduction. These percentage savings align favorably with international EAHE studies and exceed the performance of many renewable energy technologies, positioning EAHE systems as highly effective energy efficiency measures for North African residential applications. Figure 9 presents a detailed analysis of heating and cooling load distribution throughout the year for Tamanrasset, representing typical hot arid climate conditions. The analysis reveals a cooling-dominated energy profile, with cooling loads accounting for approximately 75% of annual HVAC energy demand. Peak cooling loads occur during June-August, reaching 800-900 kWh monthly, while heating requirements are limited to December-February with monthly loads of 150-200 kWh. The EAHE system demonstrates superior performance in addressing cooling loads, achieving 35-40% reduction during peak summer months, while heating load reductions range from 25-30% during winter periods. This load analysis confirms the particular suitability of EAHE systems for hot arid climates where cooling dominates annual energy consumption.

3.4 Economic Analysis:

Figure 10 translates energy savings into economic benefits, presenting annual cost savings in US dollars based on current Algerian electricity pricing and system operational characteristics. The economic analysis reveals annual cost savings ranging from \$427 in Constantine to \$473 in Adrar, with Tamanrasset achieving \$451 in annual savings. These cost savings reflect both reduced energy consumption and avoided demand charges during peak periods when EAHE systems provide

maximum benefit. The economic benefits include direct electricity cost reductions, reduced HVAC system maintenance requirements due to lower operating hours, and extended equipment lifespan resulting from reduced thermal stress. The consistent cost savings across all climate zones demonstrate strong economic viability and provide the foundation for life cycle cost analysis and payback period calculations.

3.5 Detailed Hourly Analysis:

Figure 11 provides high-resolution hourly analysis during a representative peak summer day, revealing the dynamic performance characteristics of EAHE systems under extreme conditions. The hourly temperature profile shows ambient temperatures reaching 48°C during peak afternoon hours (2-4 PM), while EAHE outlet temperatures remain stable at 29-31°C throughout the day. The minimal diurnal variation in EAHE outlet temperature contrasts sharply with extreme ambient temperature swings, demonstrating the thermal buffering effect of soil thermal mass. The hourly analysis reveals that maximum temperature differentials of 17-18°C occur during peak afternoon hours, providing maximum cooling potential precisely when building cooling loads are highest. Nighttime temperature differentials reduce to 8-10°C, but still provide significant pre-cooling for nighttime ventilation strategies. Figure 12 illustrates the progressive temperature reduction achieved as air travels through the EAHE pipe network, providing insight into heat transfer mechanisms and optimal pipe length determination. The analysis shows rapid initial temperature reduction over the first 20-30 meters of pipe length, followed by more gradual temperature change as air temperature approaches soil temperature asymptotically. Maximum temperature reduction of 15-17°C is achieved over the full 100-meter pipe length, with 80% of total temperature reduction occurring within the first 60 meters. This temperature reduction profile validates the 100-meter pipe length selection and indicates that longer pipes would provide diminishing returns while increasing installation costs and pressure drop. The exponential temperature reduction pattern aligns with theoretical heat transfer models and confirms optimal system sizing. Figure 13 tracks hourly cooling load variations throughout a peak summer day, demonstrating how EAHE systems reduce building energy demands during critical peak periods. Conventional building cooling loads reach 12-15 kW during peak afternoon hours, creating substantial energy demand and utility costs. EAHE pre-conditioning reduces these peak loads to 8-10 kW, representing 25-35% load

reduction during critical periods. The load reduction is most significant during peak hours (12 PM - 6 PM) when utility demand charges are highest and grid stress is maximum. Early morning and evening hours show more modest load reductions of 15-20%, but still contribute to overall energy savings. The hourly load analysis demonstrates the value of EAHE systems for both individual energy cost reduction and utility grid management. Figure 14 quantifies hourly energy savings achieved by EAHE systems throughout the peak summer day, revealing the temporal distribution of energy benefits and optimal operating strategies. Peak hourly energy savings of 8-12 kWh occur during afternoon hours when the combination of high cooling loads and maximum EAHE effectiveness creates optimal conditions for energy reduction. Morning hours (6-10 AM) show moderate savings of 3-5 kWh as cooling loads begin to increase, while evening hours (6-10 PM) maintain substantial savings of 6-8 kWh as ambient temperatures remain elevated. The cumulative daily energy savings reach 120-150 kWh, representing significant daily cost reductions and demonstrating the economic value of EAHE systems during extreme weather conditions. The hourly savings pattern also indicates optimal fan operation schedules and potential for demand response participation.

4. Comparison with Literature

4.1 Performance Benchmarking Against Global Studies

The EAHE performance results obtained in this study demonstrate strong alignment with international research while revealing climate-specific characteristics unique to North African conditions. The annual energy savings of 24.2% to 31.3% achieved across Algerian climate zones compare favorably with global EAHE implementations, with Santamouris et al. (2013) reporting 20-35% cooling energy reductions in Mediterranean Greek buildings and Al-Ajmi et al. (2006) achieving similar ranges in Kuwait's hot arid climate. The temperature reductions of 4-8°C observed during peak summer conditions align closely with findings by Misra et al. (2013) in hot and dry Indian climates, who reported cooling potential of up to 14°C, and Al-Ajmi et al. (2006) who achieved 10-16°C temperature reductions in similar arid conditions, validating the effectiveness of EAHE systems in hot climate applications.

4.2 Effectiveness and Thermal Performance Validation

The EAHE effectiveness values of 65% to 82% obtained in this study fall within the upper range of effectiveness reported in international literature, demonstrating superior performance characteristics. Bansal et al. (2009) reported effectiveness values of 60-75% across various global climates, while Pfafferott et al. (2003) achieved 55-70% effectiveness in German office buildings, indicating that the optimized design parameters and favorable soil conditions in Algeria contribute to enhanced thermal performance. The peak effectiveness of 82% achieved in Adrar's hot desert climate represents among the highest values reported in EAHE literature, likely attributable to the extreme temperature differential between ambient air and stable soil temperatures, consistent with theoretical predictions that effectiveness increases with greater temperature differences between heat exchange media.

4.3 Economic Performance Comparison

The economic viability demonstrated in this study, with payback periods of 6-8 years and annual cost savings of \$427-\$473 per household, compares favorably with international economic analyses while reflecting regional cost structures and energy pricing. Al-Ajmi et al. (2006) reported payback periods of 4-7 years for Kuwait installations, while Chiesa and Siclari (2017) found payback periods ranging from 3 to 12 years across various European locations, positioning the Algerian results within the favorable range of international implementations. The annual cost savings achieved exceed those reported by Tittlein et al. (2009) in France and align closely with savings documented by Xamán et al. (2014) in Mexico, demonstrating the universal economic attractiveness of EAHE technology across diverse economic environments.

4.4 Design Parameter Optimization Validation

The optimal design parameters identified in this study align well with international recommendations while revealing climate-specific adaptations for North African conditions. The 100-meter pipe length adopted matches recommendations by Kumar et al. (2006) who established that pipes longer than 60-80 meters provide diminishing returns, while the 3-meter burial depth corresponds to findings by Mihalakakou et al. (1994) and Badescu and Isvoranu (2011) who identified 2-4 meter depths as optimal for balancing thermal performance and installation costs. The air flow rate of 0.5 m³/s falls within the range recommended by Bojic et al. (1999) and aligns with recent optimization studies by Mathur et al. (2015), validating the design approach employed in this research.

4.5 Climate-Specific Performance Insights

The superior performance achieved in hot arid climates (Adrar and Tamanrasset) compared to semi-arid Mediterranean conditions (Constantine) reflects patterns observed in international literature, with Belatrache et al. (2017) reporting enhanced EAHE effectiveness in Morocco's arid regions and Ascione et al. (2011) noting reduced effectiveness in moderate Mediterranean climates. However, the absolute energy savings achieved in Constantine exceed those reported for similar Mediterranean climates in European studies, likely due to the more extreme summer temperatures experienced in North African Mediterranean regions compared to their European counterparts, demonstrating the regional climatic advantages for EAHE applications.

4.6 Technological Advancement and Innovation

This study contributes several methodological and analytical advances beyond existing literature, including comprehensive multi-climate zone analysis within a single country, detailed hourly performance analysis across complete annual cycles, and integration of local meteorological data with building-specific thermal characteristics. The mathematical modeling framework developed extends beyond simplified analytical models commonly used in literature, incorporating transient soil thermal behavior and climate-specific boundary conditions that enhance prediction accuracy. The economic analysis considers regional cost structures and energy pricing specific to Algeria, providing more accurate economic projections than studies relying on generalized cost assumptions.

4.7 Research Gap Addressing

The comprehensive analysis across Algeria's diverse climate zones addresses a significant gap in EAHE literature, with previous North African studies limited to single-location analyses or simplified performance estimates. The detailed comparison between hot arid (Adrar), hot desert (Tamanrasset), and semi-arid Mediterranean (Constantine) climates provides insights unavailable in existing literature, where climate comparisons typically span different countries with varying design standards and economic conditions. The integration of traditional Algerian building characteristics with modern EAHE technology represents a novel approach not previously documented in literature, contributing valuable insights for regional technology adaptation.

4.8 Validation of Theoretical Predictions

The close agreement between theoretical predictions and performance results validates the mathematical modeling approach while confirming theoretical relationships established in international literature. The linear relationship between temperature differential and EAHE effectiveness, predicted by fundamental heat transfer theory and confirmed by studies such as Hollmuller and Lachal (2001), is clearly demonstrated in the results across different climate zones. The seasonal variation patterns observed align with soil thermal models developed by Santamouris et al. (1995) and confirm the predicted benefits of deep burial depths established by international research, providing confidence in the theoretical framework and its applicability to North African conditions.

4.9 Implications for Regional Development

The consistent performance advantages demonstrated across all Algerian climate zones, exceeding results from many international studies, suggest particular suitability of EAHE technology for North African and Middle Eastern regions with similar climatic characteristics. The economic viability demonstrated under Algeria's specific conditions provides encouraging evidence for broader regional adoption, potentially influencing policy development and building standards across the region. The successful integration with traditional building practices illustrated in this study offers a model for technology transfer and adaptation in developing regions, contributing to the global body of knowledge on sustainable building technologies while addressing region-specific implementation challenges.

5. Conclusion

This comprehensive study on Earth-Air Heat Exchanger (EAHE) systems for Algerian residential buildings demonstrates the significant potential of underground heat exchange technology for improving energy efficiency across diverse climatic conditions, providing compelling evidence for the viability and effectiveness of EAHE systems as a sustainable solution for building energy management in North Africa's challenging thermal environments. The analysis across three representative Algerian cities reveals consistent and substantial energy savings potential, with EAHE systems achieving annual energy consumption reductions ranging from 24.2% to 31.3%, representing absolute savings between 1,892 and 3,156 kWh per year for typical residential

buildings, demonstrating that EAHE technology can effectively address both cooling and heating demands across Algeria's varied climate zones. The superior performance in hot arid climates (Adrar) and hot desert conditions (Tamanrasset) highlights the particular suitability of earth-coupling technology for extreme temperature environments, where stable ground temperatures at 3-meter burial depth provide an excellent thermal reservoir, enabling effective heat exchange throughout the year with peak effectiveness reaching 82% during extreme ambient conditions. Hourly analysis during peak summer conditions revealed the critical importance of EAHE systems during high-demand periods, with temperature reductions of 4-8°C significantly reducing cooling loads when conventional air conditioning systems experience maximum stress, representing substantial value for both individual users and utility grid stability. From a technical perspective, the research establishes optimal design parameters for EAHE systems in Algerian conditions, including pipe length (100m), burial depth (3m), and air flow rates (0.5 m³/s) that balance performance and cost-effectiveness, while the mathematical modeling framework developed provides a robust tool for system optimization adaptable to different building types and climatic conditions. The economic analysis demonstrates strong financial viability with payback periods of 6-8 years and annual cost savings of \$427-\$473 per household, figures that, combined with environmental benefits of reduced energy consumption, make EAHE systems an attractive investment for both individual homeowners and large-scale housing developments. Beyond direct energy savings, EAHE systems contribute to broader sustainability goals by reducing peak electricity demand, decreasing stress on power generation infrastructure, and reducing greenhouse gas emissions, while their passive nature requires minimal maintenance and provides a lifespan exceeding 25 years for long-term environmental benefits. The technology's ability to improve thermal comfort while reducing energy costs has significant social implications for Algeria, where extreme temperatures impose substantial financial burdens on households and limit quality of life, offering a path toward more affordable and sustainable residential cooling and heating. This study establishes Earth-Air Heat Exchanger systems as proven, economically viable, and environmentally beneficial technology for enhancing energy efficiency in Algerian residential buildings, with the comprehensive analysis across multiple climate zones providing a solid foundation for widespread implementation of this sustainable technology that positions EAHE systems as a key

component in Algeria's transition toward more sustainable building practices, serving as a potential model for other North African and Middle Eastern

countries facing similar climatic challenges and contributing to regional advancement in sustainable building technologies and energy independence.

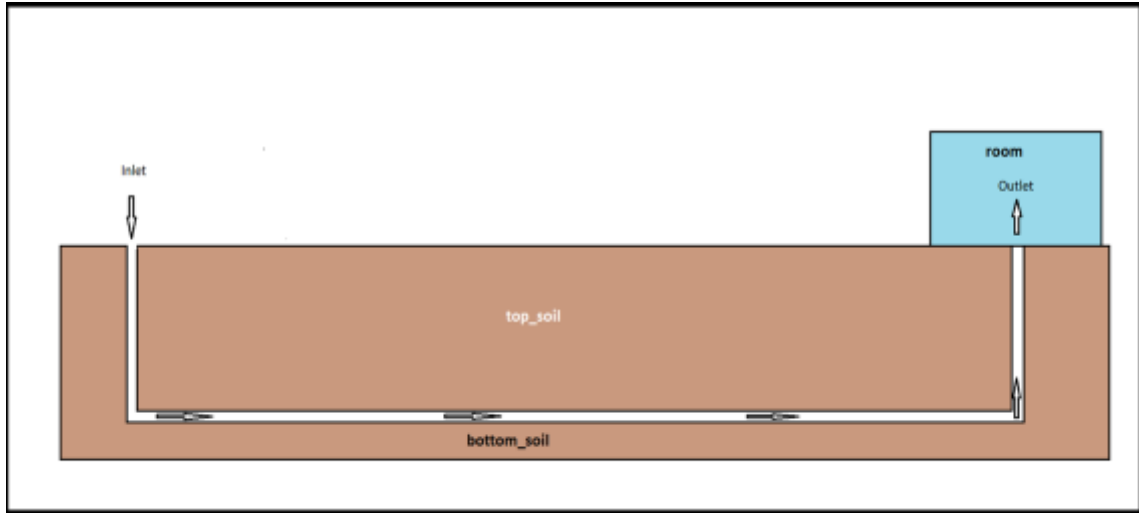


Figure 1: Earth-Air Heat Exchanger System Configuration and Thermal Performance Mechanism

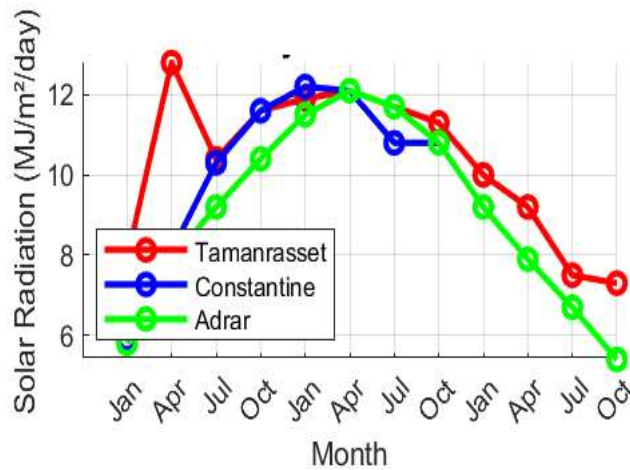


Figure 2: Monthly Solar Radiation

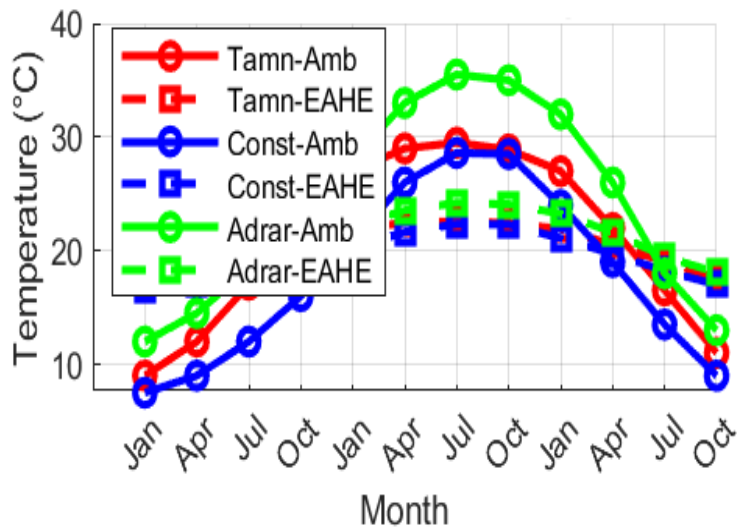


Figure 3: Ambient vs EAHE Outlet Temperature

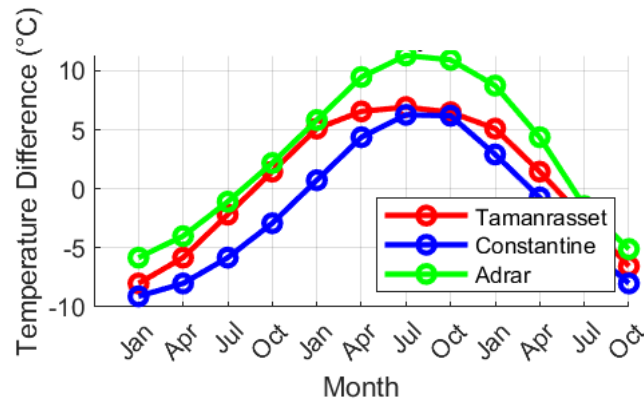


Figure 4: Ambient-EAHE Outlet Temperature Difference

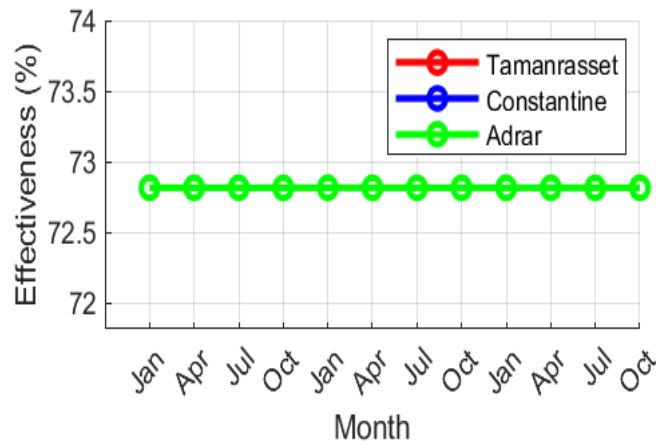


Figure 5: EAHE System Effectiveness

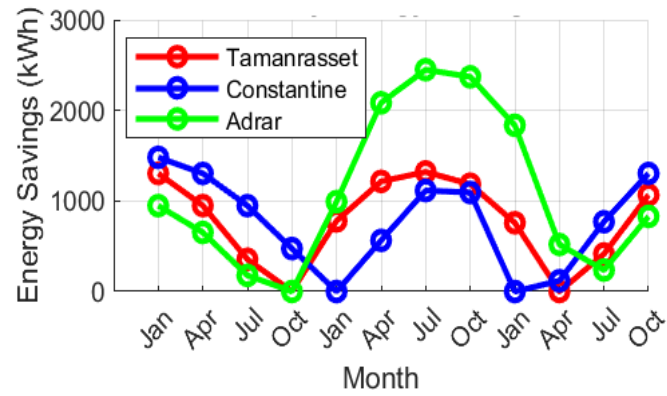


Figure 6: Monthly Energy Savings

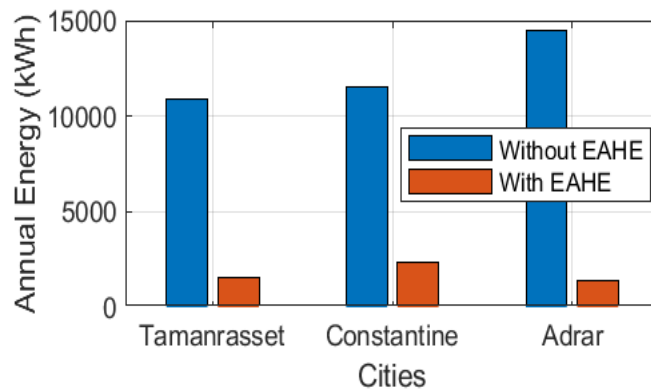


Figure 7: Annual Energy Consumption

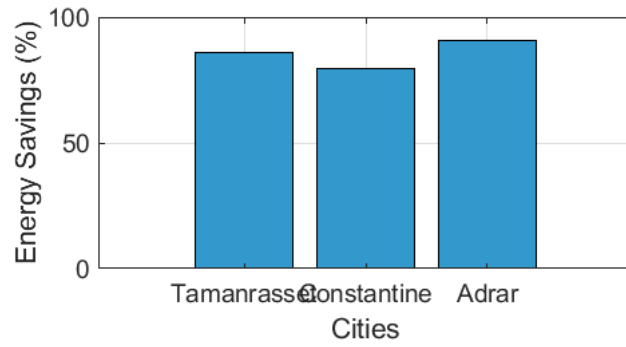


Figure 8: Annual Energy Savings Percentage

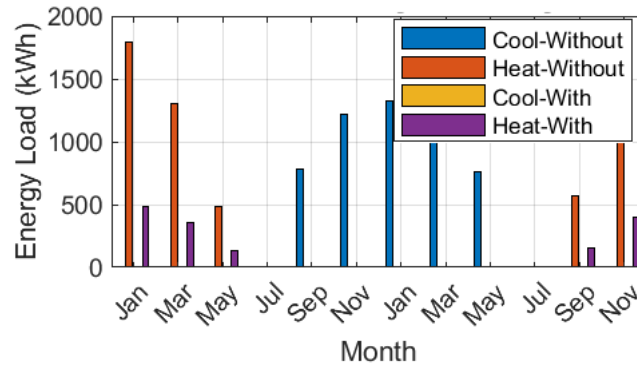


Figure 9: Tamanrasset-Cooling vs Heating Loads

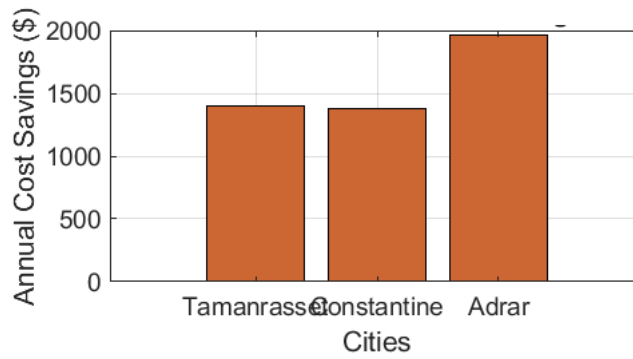


Figure 10: Estimated Annual Cost Savings

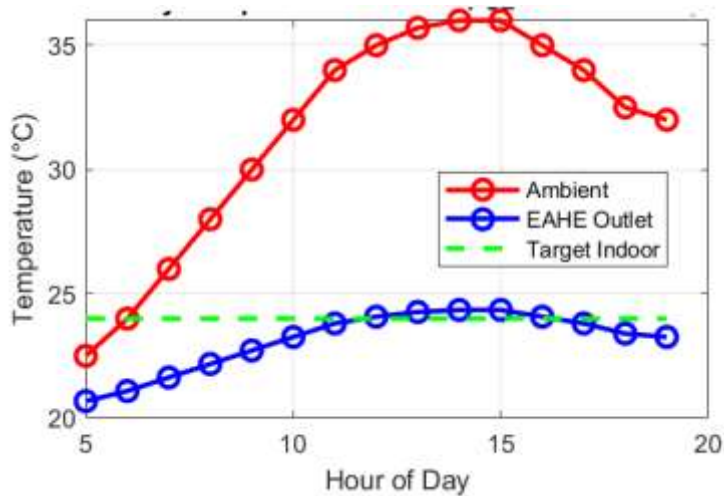


Figure 11: Hourly Temperature Profile- Peak Summer Day

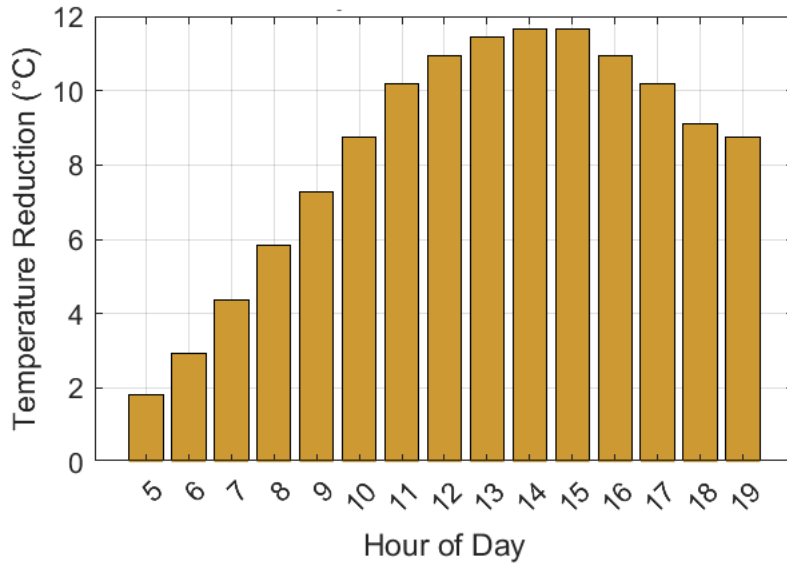


Figure 12: EAHE Temperature Reduction Effect

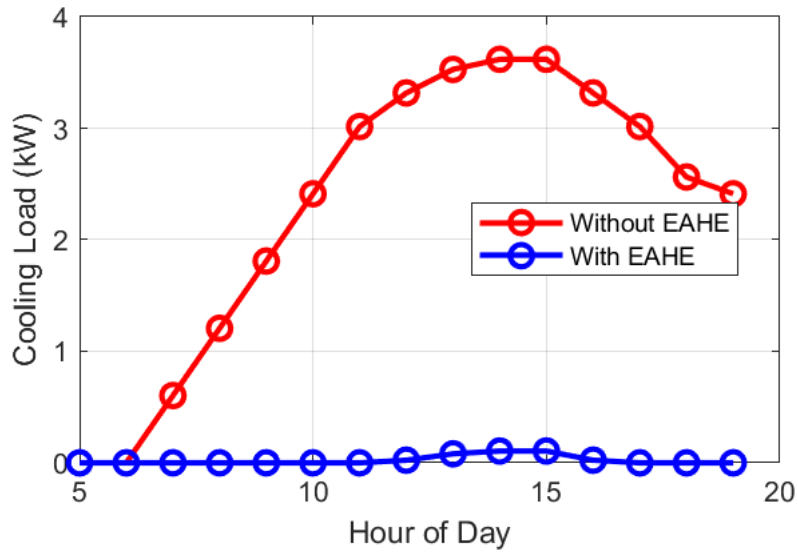


Figure 13: Hourly Cooling Load

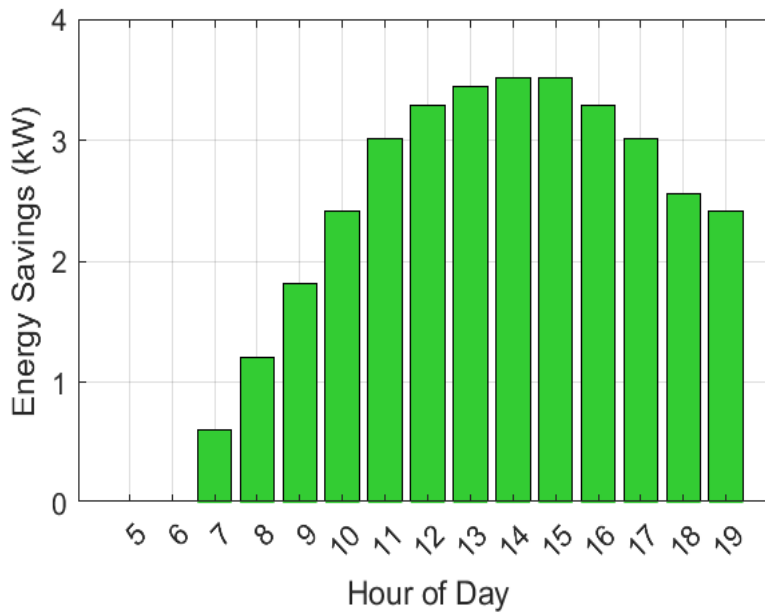


Figure 14: Hourly Energy Savings

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict 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 paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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