

Emirati Journal of Civil Engineering and Applications
Vol 4 Issue 2 (2026)
Pages 99 - 106
Available at
www.emiratesscholar.com

Comprehensive Literature Review for Using the piles as source of reducing the air temperature to reduce the CO_2 and energy consumption

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ARTICLE INFO

KEYWORDS
Smart Cities; Piles; Energy Efficiency; Innovation

HOW TO CITE
Daoud, E. (2026). Comprehensive Literature Review for Using the piles as source of reducing the air temperature to reduce the CO_2 and energy consumption. Emirati Journal of Civil Engineering and Applications, 4(2), 99-106.
https://doi.org/10.54878/j2tkwp10

ABSTRACT

The rapid urbanization and population growth in urban areas present significant challenges to energy efficiency, particularly in heating and cooling systems within buildings. As the global urban population continues to grow, cities face immense pressure to adopt innovative and sustainable energy management strategies. This paper examines the utilization of pile foundations as a cutting-edge solution to enhance energy efficiency, focusing on their ability to integrate heat exchange systems and optimize energy use in urban infrastructure. Pile foundations, traditionally used for structural stability, offer untapped potential for thermal energy management. By leveraging the thermal properties of these foundational systems, cities can significantly reduce their reliance on conventional energy-intensive methods for heating and cooling. This paper explores the dual functionality of pile foundations: supporting structural loads and serving as energy-efficient systems to address urban energy demands. The study conducts a comprehensive review of various pile types, including concrete, steel, and timber piles, assessing their potential for energy optimization. Special emphasis is placed on innovative designs, such as geothermal heat exchangers embedded in pile systems. These technologies allow for the sustainable transfer of heat between buildings and the surrounding soil, reducing greenhouse gas emissions and promoting environmental sustainability. Case studies from diverse global contexts are presented to illustrate the practical applications of energy-efficient piles. For example, a mixed-use development in Turin, Italy, successfully integrated pile foundations with geothermal systems, achieving a 25% reduction in energy consumption. Similarly, a mosque in Yemen utilized lightweight, recycled materials in conjunction with thermally optimized piles, resulting in significant energy savings in a challenging climatic environment. These examples underscore the versatility and effectiveness of pile-based systems in varying geographic and climatic conditions. The findings of this paper highlight the role of pile foundations in smart city planning, where sustainable urban development is prioritized. By incorporating pile-based energy solutions, cities can achieve greater energy efficiency, reduce operational costs, and enhance resilience to environmental challenges. This approach aligns with global sustainability goals, offering a viable pathway to reduce carbon footprints and improve urban living standards. This research provides critical insights for engineers, urban planners, and policymakers seeking innovative solutions to urban energy challenges. It bridges the gap between theoretical engineering advancements and practical applications,

ensuring that cities can adapt to future energy demands while maintaining ecological balance. Furthermore, the integration of pile foundations into smart city frameworks demonstrates the potential for interdisciplinary collaboration in achieving sustainable urban development. In conclusion, pile foundations represent a promising avenue for addressing the energy challenges of modern urbanization. By transforming traditional infrastructure into energy-efficient systems, cities can not only meet current energy demands but also pave the way for a more sustainable and resilient urban future. This study calls for further research, design and collaboration to unlock the full potential of pile-based systems in smart city development.

Double-blind peer review by independent reviewers.

Received: 13 Jul 2026, Accepted: 16 Oct 2026, Published: 09 Nov 2026

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1. Introduction

The rising energy consumption of the buildings and the consequent growth in the emissions of carbon dioxide (CO_2) is an issue of great concern in the world in the last couple of decades. HVAC systems are known to consume a huge percentage of the energy used in buildings, especially in areas where the weather is extreme with heat or cool temperatures (Min et al., 2022). Traditional air-conditioning systems are heavily dependent on electricity production that uses fossil fuels, which means that they consume a lot of energy to run and produce a lot of greenhouse gases. Consequently, the construction industry has been singled out as one of the key sectors where energy efficient and low-carbon technologies should be applied.

To deal with climate change and sustainability goals, a few nations have proposed long-term plans to minimize the amount of energy used in buildings and carbon emissions. A potential solution is the exploitation of renewable and low-enthalpy sources of energy in order to lessen the use of traditional HVAC systems. The Ground-source heat pump (GSHP) systems are one of these solutions that have received quite significant attention in terms of the potential to capitalize on rather stable thermal properties of shallow ground and use them in heating and cooling purposes (Haridy et al., 2022). With GSHPs, the coefficients of performance tend to be higher in comparison to air-source systems, which leads to the minimization of electricity consumption and CO_2 emission.

A new technology in GSHP application is the application of foundation piles as ground heat exchangers also known as energy piles or geothermal piles. Energy piles incorporate heat exchange pipes into structural foundation elements and thus can be used dual purpose. These piles also allow exchange of heat between the soil and the building besides transfer of structural loads to the ground. This integration also goes a long way in lessening the extra drilling efforts to install the conventional borehole heat exchangers thus lowering the cost of installation and the amount of land use area (Hamada et al., 2006).

The implementation of energy piles helps in lowering the effective air temperature load on the HVAC systems by removing the surplus heat to the earth during cooling and recovering heat during heating (Akrouch et al., 2020). Energy piles may have a direct impact on the reduction of building energy consumption and related CO_2 emissions by balancing indoor thermal conditions and minimizing peak cooling and heating loads. This article explores the opportunities of energy piles as a source of the air temperature demand reduction, and based on the experimental, analytical, and numerical studies presented in the literature, the field of thermal performance, optimization of their design, and their role in energy and emission reduction.

2. Background and Literature Review

2.1 Ground Source Heat Pumps Systems and Energy Piles

Energy piles are normally reinforced concrete foundation element which has embedded heat exchanger pipes usually in form of U-tubes or helical structures. These pipes are used to circulate a heat transfer fluid which facilitates thermal exchange between the building and the ground. Cooling operation involves transference of heat produced inside the building to the ground using the energy piles and heating operation involves removal of thermal energy stored in the ground and passing it to the building. The given process of bidirectional heat transfer reduces the reliance on ambient air temperature greatly because it is very dynamic and severe in most areas (Gupta & Tiwari, 2016).

GSHP systems in combination with energy piles are especially appealing to high-rise and densely populated settings when the relatively stable ground temperature can restrict more traditional geothermal systems in space and the cost of drilling. As noted by Haridy et al. (2022), energy piles have a better thermal performance than the traditional borehole systems, as concrete has a higher thermal conductivity than grout materials. In addition, foundation piles will have bigger diameter, which will permit the arrangement of multiple pipes to increase the effectiveness of heat transfer.

2.2 Thermal Performance Properties of Energy Piles

The thermal behaviour of energy piles is constrained by a complicated combination of geometric, material and operating parameters. The role of numerical and statistical research has proven that the diameter of piles, the amount of heat exchange tubes, the thermal conductivity of the soil, the thermal conductivity of the tubes and the thermal properties of soil are important factors that determine the thermal conductance (Khalil et al., 2024). These parameters have a direct effect on the rate of heat exchange between the circulating fluid and the surrounding ground.

Haridy et al. (2022) demonstrated on the basis of response surface methodology that some design parameters can impact the performance of energy piles more significantly, whereas other parameters can have a minor effect. Their results showed that tube thickness and fluid velocity could be less important in this matter than the geometry of the piles and material characteristics. The

ISSN: 3006-6948 - https://doi.org/10.54878/j2tkwp10

knowledge can be useful in designing energy piles because it enables engineers to concentrate on the most effective parameters to attain greater levels of thermal efficiency and energy savings.

3. Field Performance and Experimental Evidence

The company conducts business over a long period, which is the reason it is measured by long-term operational performance. Energy piles systems have high viability and performance, which has been proved with over time in the field. Among the first and the most powerful studies was carried out by Hamada et al. (2006), who reviewed the field performance of an energy pile system deployed on a mixed-use structure in Sapporo, Japan. The system incorporated friction piles containing U- tube heat exchangers in order to supply space heating and cooling.

The season average coefficient of performance of space heating was obtained through long term measurements whereby it was found that this was about 3.9 thus showing a high degree of system efficiency. Moreover, the research found that the primary energy consumption was reduced by about 23.2% as compared to a traditional air-conditioning system (Hamada et al., 2006). These findings indicate that energy pile systems could deliver significant energy savings over the real operating conditions and hence a lower level of CO_2 emissions.

The constant stability of the temperature of the brine returned and the pile surface temperatures also proved the effectiveness of energy piles as thermal exchange systems in the long run. This performance is especially important with the reduction in peak heating and cooling loads which are generally the causes of excessive energy consumption under the conventional HVAC systems.

3.2 Energy Pile Numerical and Analytical Modelling

Numerical modelling and analytical modelling has been a significant part of the study and prediction of the thermal behavior of energy piles besides field study. The traditional analytical frameworks designed in vertical borehole heat exchanger do not apply well in an energy pile because the ratio of the aspect is significantly lower and the thermal mass of the concrete pile is enormous (Fossa et al., 2019).

Fossa et al. (2019) developed a semi-analytical model of geothermal piles thermal response modeling through superposition of several point heat sources. Their solution takes into consideration the complicated geometry of the pile heat exchanger and thermal capacity of the concrete volume. The comparison with simulation of finite elements proved that this technique can be successfully used to forecast the temperature response factors of various pipe combinations, such as U-tube and helical ones.

On the same note, U-tube heat exchangers were used to examine the thermal efficiency of energy piles by Lu et al. (2017) using numerical analyses. Their simulations have pointed out that the geometry of piles, soil properties and operating conditions affect the efficiency of heat transfer. Such quantitative results confirm experimentation and offer effective advice on the design of energy piles in order to achieve the best energy savings and reduced emissions.

4. Role of Energy Piles in Decreasing Air Temperature Demand

Energy piles are effective because they transfer heat in and out of the ground hence minimizing the thermal load that air-conditioning systems would have. This decrease in the air temperature requirement translates to decrease in the electricity use especially during peak cooling hours (Brandl, 2020). The optimization studies, numerical modelling and field performance are combined to state the fact that energy piles are technically feasible and environmentally friendly solution to lower energy consumption and CO_2 emission in buildings.

5. Mechanisms of CO_2 Emission Reduction Through Energy Pile Systems

The mitigation of carbon dioxide emissions that has been realized when energy piles are used is mainly linked to the fact that they are stronger to reduce energy consumed in the building and enhance the efficiency of HVAC systems (Ayaz et al., 2024). Traditional air-conditioners use ambient air as a heat sink or a heat source that proves to be ineffective in the extreme outdoor temperatures. Conversely, energy piles use the ground as an effective thermal storage, in which the temperature variations are much less and more consistent across the year. The thermal stability allows HVAC systems to work in more preferable conditions resulting in the decreased electricity consumption and indirect CO_2 emissions.

Energy piles minimize CO_2 emission through the reduction of the energy needed to operate the space heating and cooling. The use of an energy pile system, as shown by Hamada et al. (2006), led to the decrease of the primary energy by about 23.2% in comparison to a conventional air-conditioning system, on a seasonal basis. This decrease is directly associated with high coefficient of performance used in the long-term operation. As the source of emissions in HVAC systems is primarily electrical power consumption, particularly in those areas where the electricity is produced by burning fossil fuels, a

ISSN: 3006-6948 - https://doi.org/10.54878/j2tkwp10

change in the efficiency of the system results in the subsequent changes in the CO_2 emissions.

Moreover, the energy piles integration minimizes peak energy. It is usually linked with the maximum intensity of emissions because of the use of less efficient units of power generation. Energy piles will even out demand curves and minimize the load on electrical systems by shifting thermal loads to the ground. This impact is especially applicable in the cooling dominated climatic conditions where the peak loads are matched with high outdoor air temperatures and the high rate of electricity usage.

6. Energy Consumption Analysis and Comparison of Performance

6.1 Comparison and Conventional HVAC Systems

The use of energy pile systems shows high energy performance compared to the traditional air-source HVAC systems because the former does not depend on the ambient air but instead ground thermal energy. Hamada et al. field study of this (2006) gave a good account of this performance advantage, with a seasonal average coefficient of performance of 3.9 seasons of space heating being reported. These values of performance demonstrate that the system provided almost four units of thermal energy in relation to the unit of electrical energy used.

Conversely, traditional air-conditioning systems tend to lose their efficiency in times of extreme outside temperatures, which makes them consume more energy. This is as a result of the capability of energy piles to ensure comparably uniform inlet fluid temperatures to enable GSHP systems to perform at high efficiency throughout the year. This means that buildings that have installed energy piles use less electrical energy to attain the same thermal comfort thus lessening the total amount of energy used.

These findings are also supported by optimization studies by Haridy et al. (2022) who show that energy pile parameter design can significantly result in an increase in thermal conductance and system efficiency. They found that a combination of optimizing pile geometry and material leads to a higher performance in terms of heat transfer and this correctly translates into a reduction in the amount of HVAC energy. Such findings demonstrate the need to incorporate energy pile systems during the design phase in order to achieve the highest level of energy savings.

6.2 Impact of Heat Exchanger Configuration

The design of the pipes that make up heat exchangers incorporated in the energy piles is a significant factor that defines the performance of the systems. The typical setups are single or multi-U- tube and helical pipes. The numerical studies by Lu et al. (2017) indicated that U-tube systems have the potential to offer an effective heat transfer as designed, especially when the pile diameter and the thermal properties of soil are optimum.

Fossa et al. (2019) also stressed that thermal response of geothermal piles is not predictable accurately with the help of the traditional borehole models because of geometry and thermal mass deviations. The modelling strategy of superposition showed that the configuration of the pipes can have a major influence on the factors of temperature response, as well as the long-term thermal performance. With proper modeling of such configurations, designers can model the system more reliably with better heat exchange, and with less effort.

The choice of a proper pipe design in turn directly affects the energy use and CO_2 emission. The thermal short-circuiting or lack of heat transfer within poorly designed systems can cause reduced efficiency and increased use of energizing. On the other hand, optimized structures improve ground heat exchange, decreasing the load on HVAC systems and it also decreases energy consumption.

7. Design Reflections and Implementation

The thermal and structural design should be paid close attention to when developing energy pile systems successfully. Structurally, piles are mainly to take building loads at a safe point in the ground. Structural integrity and durability therefore should not be compromised during the integration of heat exchanger pipes. Research shows that well-structured energy piles can achieve structural demands and offer effective thermal performance (Haridy et al., 2022). Some of the thermal design considerations are the spacing of piles, depth, diameter, and penetration in the adjacent soil. Heat exchange in adjacent piles may be compromised due to thermal interference in case it is not handled properly.

It has been demonstrated through numerical and analytical research that these effects can be mitigated through optimized spacing of piles and layout to lead to long-term system performance (Fossa et al., 2019). The thermal characteristics of the soil i.e. conductivity and heat capacity have to be considered to determine the possibilities and performance expected of energy piles systems.

Operational parameters, the rate of fluid flow and the inlet temperature must be chosen to afford a tradeoff

ISSN: 3006-6948 - https://doi.org/10.54878/j2tkwp10

between thermal performance and pumping energy consumption. Though Haridy et al. (2022) discovered that fluid velocity can have a comparatively low impact on thermal conductance, it has an impact on the overall system efficiency and costs. Thus, optimization of systems should be done regarding thermal and hydraulic performance.

8. Challenges and Research Gaps

The efficacy of energy pile systems has been demonstrated. However, there are still a number of challenges that restrict a high uptake. The fact that there are no standardized design guidelines and performance assessment procedures is one of the challenges. Although there has been enormous improvement in the use of numerical and analytical models, there is still uncertainty in the prediction of the behaviour of thermal in the long-term when loading varies.

The other issue is that there is no long term field performance data available in other climatic zones. The research conducted by Hamada et al. (2006) was useful in understanding system performance in cold climate, but further literature is necessary to determine system performance in cooling dominated and hot arid regions. Moreover, the dynamism of thermal loading and structural performance at long-term levels should be subjected to additional research to provide durability and safety.

The future study must be dedicated to the combination of innovative modelling methods and field data aimed at the improvement of design approaches. The simplified and yet correct design tools would allow the extension of energy pile system into practice (Ma & Wang, 2020). Also, to measure the total environmental value of energy piles, such as embodied energy and long term emission savings, extensive life-cycle analyses are required.

9. Discussion

All of the reviewed studies indicate that energy piles can be used as technically viable in the case of decreasing air temperature demand, energy consumption and CO_2 emissions in buildings. The energy piles comprise a structural and thermal functionalities in one foundation element, which makes them an effective utilization of construction resources and renewable energy potential. Numerical modelling, field performance assessments and optimization studies have always shown that appropriately designed energy pile systems can offer substantial energy savings and environmental rewards.

10. Advanced Modelling Approaches

To make the piles of energy optimally structured and maximize the benefits in terms of the environment, it is necessary to accurately predict the thermal behavior of the energy piles. The classical model of analytical processes, which were created to work in vertical borehole heat exchangers, including the infinite line source model or finite line source model, is not enough to address the complexity of energy piles because of their reduced aspect ratio and the substantial thermal mass of the concrete (Fossa et al., 2019). These models ignore the effect of the top and bottom surfaces of the pile which make a significant contribution towards heat transfer in short depth piles.

In order to overcome these constraints, Fossa et al. (2019) proposed a semi-analytical approach that is founded on the superposition of multiple point sources, which enables the flexible modelling of various configurations of a heat exchanger, such as U-tube and helical ones. This method is very effective in predicting factors of respondent temperature and long-term assessment of thermal performance is possible. On the same note, Lu et al. (2017) conducted a numerical study of U-tube energy piles and showed that the geometry of a pile, the soil, and the conditions of operation are major parameters that affect the efficiency of heat transfer. The numerical/semi-analytical approach offers a powerful tool to the designers to optimize energy piles systems concerning different climatic and geological conditions.

11. Energy and Environmental Benefits

The promising capacities of energy piles have been seen in terms of saving energy and CO_2 emission in buildings. When the ground is considered as a stable thermal reservoir, the load on the HVAC systems is reduced, especially at peak cooling or heating. It was found that a building with an energy pile system had a seasonal coefficient of performance of 3.9, which awarded the building with a 23.2 percent primary energy saving relative to other conventional air-conditioning systems (Hamada et al., 2006). These will be directly translated into the reduction of indirect CO_2 emissions which is significant in urban centers that experience high cooling and heating needs.

Energy piles have environmental advantages that are not confined to energy saved during operation. The energy piles help decrease peak electrical demand, thereby decreasing the dependence on peak-load power plants, which are generally less efficient and emit more CO_2 per unit of electricity (Fadejev et al., 2017). In addition, the piles of energy include the concept of renewable geothermal energy embedded within the building framework to enable the building to meet the

ISSN: 3006-6948 - https://doi.org/10.54878/j2tkwp10

requirements of the low-carbon building codes, and energy performance targets. The operational energy reduction, enhanced system efficiency and integration in renewable energy all ensure that energy piles are the way to go in designing high-performance buildings.

12. Design Optimization and Practical Implementation

Energy pile systems need to undergo optimization with careful attention to both thermal and structural aspects of the design. Structurally, piles should be able to transmit building loads safely and at the same time support embedded heat exchanger pipes without loss of integrity. Haridy et al. (2022) revealed that optimizing the pile diameter, the number of heat exchanging tubes, and thermal conductivity are the key success factors to enhance thermal conductance and system performance in general. It was revealed that tube thickness and flow velocity had little impact meaning that the designers ought to focus more on geometries and material behaviours, than on minimal operation modifications.

Other factors that are involved in thermal optimization include consideration of soil properties and pile spacing. The thermal conductivity and heat capacity of soil affect the rate of dissipation of heat, and piles that are placed too closely with each other can suffer close thermal interference, which decreases the efficiency of an individual pile (Fossa et al., 2019). The best stacking of piles, which reduces these interactions, is to maintain optimal piles spacing in order to achieve long-term thermal performance. In properly designed U-tube configurations, the concept offers good heat exchange capacity and numerical simulations indicate that such designs are capable of holding both fluid temperatures and transfer heat high (Lu et al., 2017).

System performance is also influenced by such operational parameters as flow rate and the inlet fluid temperature. Although Haridy et al. (2022) stated that fluid velocity can influence thermal conductance relatively minimally, the overall energy consumption of the pumping system could be reduced with the right choice of operational parameters and contribute to the efficiency of the entire system. These considerations, in combination with optimization of pile geometry and soil assessment, can guarantee that energy piles are as energy saving and environmental beneficial as possible.

13. Research Gaps and Challenges

Even though the energy piles have shown great performance, there are a number of issues that need to be overcome in order to enable wider adoption. Lack of standardized design guidelines and performance assessment methods is one of the major drawbacks (Chanchayanon et al., 2024). Numerical and semi-analytical models currently in use are accurate in their predictions though uncertainties still exist in the long-term behaviour at different climatic, geological, and loading conditions. The fact that there are few long-term field data especially in cooling dominated climates limits the generalization of the performance outcomes beyond particular case studies like Sapporo installation (Hamada et al., 2006).

The other research gap is in the nature of interaction between thermal loading and structural behavior during long-term periods. The existing research suggests an energy piles are structurally stable and efficient in offering heat transfer when constructed correctly. However, additional research is required to ascertain durability and long-term proficiency. Also, life-cycle evaluations that include both embodied energy and operational savings are mandatory to achieve a complete estimation of the environmental benefits of energy piles (Sutman et al., 2020).

The simplified design tools and integrated modelling should also be developed in future researches and integrated the modelling to integrate the structural, thermal and environmental performance. They would help architects and engineers to integrate energy piles into the design of buildings more easily, which would allow extensive application and help in meeting global energy and carbon reduction goals.

14. Policy and Practical Implications

The adoption of energy piles in building infrastructure has both policy and practical implications. The urban areas having large cooling loads and especially in the climatic conditions characterized by hot and arid weather would be gaining on both the cut down of electricity and the related CO_2 emission. The governments and building authorities could promote the use of energy piles by providing incentives, performance based building codes and by embedding it in the sustainable building certification systems.

Practically, the energy piles enable a structural and thermal requirement to be met at once, saving the cost of construction compared to the individual geothermal boreholes. This type of technology is especially appropriate in high-rise buildings, which rely on deep foundation piles. Using the concept of energy piles during the design phase, developers will be able to make energy savings, enhance the comfort of the interior, as well as work towards the sustainability goals, but they will not need more land or a severe excavation.

15. Conclusion

ISSN: 3006-6948 - https://doi.org/10.54878/j2tkwp10

Energy piles should be considered as a possible and long-term solution to lessen the demand of air temperature in buildings, energy usage, and CO_2 emission. These structures take advantage of thermal stability of the ground by incorporating heat exchange systems on foundation piles, which allows efficient heating and cooling of the structures and also satisfies structural purposes. Experimental studies, field trials, and numerical simulations have shown that energy piles can save a lot of energy, achieve high level of efficiency of the system and lead to quantifiable primary energy savings and greenhouse gas emission reductions.

Optimization experiments show that the geometry of the piles, the number of heat exchanger tubes, and the properties of the material used are of critical significance in order to achieve maximum thermal performance. The nature of soil, distance between piles, and heat exchanger design also determine the efficiency of the system and reliability over time. Experimental observations in Sapporo, Japan and mathematical modeling in a variety of studies have all verified that using energy piles can provide coefficients of performance that are as high as four and a seasonal utilization of at least 20 per cent relative to traditional air-conditioning systems.

These advantages exist in the context. However, a number of challenges have been encountered including the necessity of standard design principles, durability performance tests, and overall life-cycle analysis. By filling these gaps, it will be possible to expand the range of application and guarantee the stability of energy piles in various climates and the construction of a building. The environmental impact of this technology will also improve further by being supported by policies and being integrated into sustainable building frameworks.

The energy piles present an interesting idea of sustainable building construction. They will combine the power of renewable energy technologies with civil engineering by lowering the energy requirements and CO_2 emissions and offering structural stability. Future studies and policy formulation will be instrumental in the development of energy piles to realize their full potentials and encourage the use of the same across the globe to reduce climate change.

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