



Energy Performance Assessment of Energy Pile Systems for Heating and Cooling Demand in Residential Buildings: A Case Study in Tehran

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ARTICLE INFO	ABSTRACT
Article History: Received 3 February 2024 Received in revised form 17 April 2025 Accepted 26 July 2025 Available online 2 September 2025 Keywords: Shallow geothermal energy; Energy pile system; Taguchi method; ANOVA; Carbon Emission Estimation.	Energy piles, which combine the structural role of building foundations with ground-source heat exchange, offer a promising means of reducing building energy use. This study evaluates the thermal performance of an energy pile system integrated into an eight-story residential building in the Saadat Abad district of Tehran, Iran. A Taguchi L9 orthogonal array was used to examine the effects of three design parameters (pile depth, pile diameter and heat exchanger pipe diameter), each at three levels, on the thermal response of an array of 16 energy piles, and the nine resulting scenarios were simulated in PileSim 2. Pile depth was the most influential parameter, followed by [pile diameter] and [pipe diameter]. In the optimal configuration, the 16 piles supplied approximately 97% of the building's heating demand and 61% of its cooling demand. A preliminary estimate based on emission factors reported in the literature indicated that the optimal system could reduce annual CO₂ emissions by about [X] t ([Y]%) compared with a conventional [gas boiler and split air-conditioning] system. The findings show that energy piles can meet a substantial share of residential heating and cooling demand under Tehran's climatic conditions. Because the results are based on numerical simulation, field monitoring is recommended to validate the predicted performance.

1. INTRODUCTION

The rapid growth in global energy demand within the building sector, together with the progressive depletion of conventional fossil fuel resources, has intensified the search for cleaner and more sustainable energy technologies. Buildings currently account for approximately 40% of the total global energy consumption and are responsible for over 30% of worldwide greenhouse gas emissions [1]. This considerable environmental impact highlights the urgent need for high-efficiency and low-carbon solutions capable of meeting the heating and cooling requirements of modern buildings. Among various renewable energy strategies, shallow geothermal systems have attracted increasing attention as reliable and environmentally sustainable sources of thermal energy. One of the most promising approaches in this category is the use of energy piles, in which structural foundation piles simultaneously

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serve as ground heat exchangers. Owing to the relatively stable temperature of subsurface layers at depths of approximately 6–8 m, energy piles enable efficient thermal exchange between the soil and building foundations [2]. When integrated with a ground source heat pump (GSHP), these systems can extract heat from the ground during winter and reject excess heat back into the soil in summer, thereby maintaining stable year-round thermal conditions [3]. A typical energy pile installation comprises reinforced concrete foundation piles embedded with heat exchange pipes, a geothermal heat pump unit, and an internal distribution network for transferring thermal energy throughout the building [4]. As illustrated in Figure 1, the main components of a GSHP system utilizing energy piles include the pile heat exchangers, the heat pump unit, and the building's heating/cooling circuit [6]. Through their dual structural and thermal functionality, energy piles offer significant advantages in terms of energy efficiency, land utilization, and reduction of dependence on conventional HVAC systems [5]. Consequently, they have emerged as a promising solution for sustainable building design. Motivated by these benefits, the present study investigates and models the thermal performance of an energy pile system designed for a residential building located in Tehran.

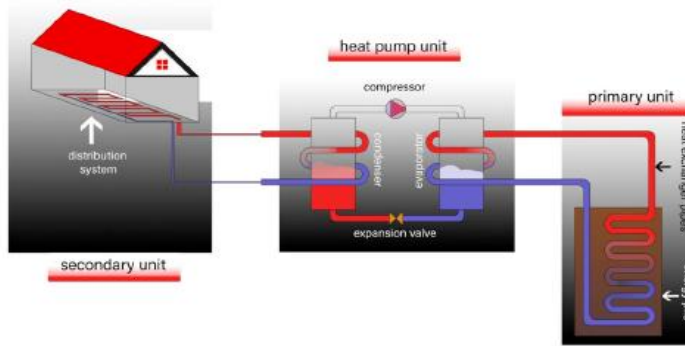


Fig. 1. Schematic of a ground source heat pump system with energy piles [6].

2. LITERATURE REVIEW

The concept of integrating heat-exchange functionality into structural foundation piles was first proposed in the 1980s as an approach to reduce the drilling costs associated with conventional geothermal systems [7]. This technique, now widely recognized as the energy pile system, has since evolved into an efficient and space-saving solution for harvesting shallow geothermal energy, particularly in densely built urban environments where available land is limited [8]. By embedding heat exchange pipes within reinforced concrete piles, energy piles fulfill a dual function: they provide structural support while simultaneously enabling thermal interaction with the surrounding ground. The thermal performance of energy piles is influenced by a complex set of interdependent parameters, including pile geometry and spacing, pipe configuration, fluid flow characteristics, the thermal properties of concrete, and the thermal–moisture conditions of the surrounding soil. Previous research has consistently indicated that increasing pile length and diameter enhances the heat transfer capacity, whereas thermal interference among piles in grouped configurations can significantly affect the coupled thermal and mechanical behavior of the system [9]. Pipe layout has also been identified as a critical design parameter; configurations such as W-shaped and helical arrangements typically yield higher thermal performance compared with conventional U-shaped configurations, although they may require more complex installation procedures and higher associated costs [10]. Fluid flow characteristics within the heat-exchange pipes represent another key determinant of overall efficiency. Studies have shown that operating within the transitional flow regime can offer an optimal compromise between enhanced heat transfer and acceptable pumping power demand [11]. In addition, the thermal conductivity of concrete has a substantial impact on system performance, higher conductivity values generally improve heat transfer; however, excessive incorporation of conductive additives may adversely affect the mechanical integrity of the concrete, necessitating careful material optimization [12]. The long-term behavior of energy pile systems is strongly governed by soil thermal properties and moisture content, which influence both heat dissipation and seasonal thermal recovery processes [13]. In recent years, a growing body of literature has focused on comprehensive performance assessments

of energy pile systems, integrating energy, exergy, economic, and environmental evaluations. Advanced optimization and modeling techniques, including genetic algorithms, detailed numerical simulations, and Taguchi-based design methods, have been employed to enhance system configuration and operational performance [14]. Despite these advancements, many existing studies have predominantly examined isolated performance aspects or idealized single-pile configurations. A notable research gap persists regarding the integrated assessment of energy performance and environmental impacts for realistic multi-pile systems, particularly under urban climatic conditions such as those of Tehran [15]. To address this gap, the present study numerically simulates and evaluates the energy performance of a practical sixteen-pile energy pile system designed for a residential building in Tehran. Furthermore, the associated environmental benefits stemming from reduced dependence on conventional energy sources are quantitatively assessed. This integrated framework provides a more realistic and application-oriented understanding of the potential of energy pile systems in real-world urban environments.

3. METHODOLOGY

In this study, the performance of an energy pile system was evaluated using an energy-assessment framework based on numerical modeling and design of experiments. The analysis began with the development of a numerical model in PileSim 2, which was first validated using published reference data from the energy pile system implemented at Zurich Airport [16]. This validation step ensured the reliability of the numerical approach in predicting ground heat exchange behavior. Subsequently, the heating and cooling loads of the selected eight-story residential building was determined using Design Builder. The simulated energy demand was compared with the building's actual energy consumption records to verify the accuracy of the load estimation. Afterward, an appropriate ground-source heat pump (GSHP) was selected, and the thermal properties of the soil together with the operational parameters of the heat pump were incorporated into the simulation environment. Based on the structural layout of the building, a configuration consisting of sixteen energy piles was modeled as the geothermal heat exchange system. To systematically investigate the influence of key design parameters, three primary factors, pile depth, pile diameter, and heat-exchange pipe diameter, were selected as the main design variables. These parameters were analyzed using the Taguchi design of experiments method, through which several representative simulation scenarios were defined to examine the thermal performance of the system under different configurations. The simulation outputs were subsequently evaluated using the Taguchi analysis framework and analysis of variance (ANOVA) in order to identify the most influential parameters affecting system energy performance and to determine the optimal configuration. Finally, a preliminary estimation of carbon emission reduction was conducted only for the optimal configuration, using emission factors reported in Reference [17]. This additional step provides an initial indication of the environmental benefits associated with the proposed system. However, it does not constitute a comprehensive life-cycle assessment or full carbon balance analysis, which falls beyond the scope of the present study.

3.1. Model Validation

In this study, the performance of an energy pile system was examined through an integrated energy and environmental assessment framework. The analysis commenced with the development of a detailed numerical model in PileSim 2, which was validated against published case data from the well-documented energy pile installation at Zurich Airport [16]. This validation ensured the reliability and predictive accuracy of the simulation approach for characterizing ground heat exchange behavior. Following model validation, the heating and cooling demands of the target residential building were estimated using Design Builder. The simulated energy consumption was cross-verified against the building's actual utility bills to confirm the accuracy of the load estimation. Once the thermal loads were defined, an appropriate ground source heat pump (GSHP) was selected. The relevant soil thermal properties and operational parameters of the heat pump were subsequently integrated into the simulation environment to reproduce realistic operating conditions.

According to the structural layout of the building, a configuration consisting of sixteen energy piles was modeled. To systematically evaluate the effect of key design variables, three parameters, pile depth, pile diameter, and heat-exchange pipe diameter, were selected as the primary design factors. These parameters were investigated using the Taguchi design of experiments (DOE) method, through which several representative scenarios were defined and simulated to analyze the thermal behavior of the system under varying configurations. The simulation results were

further analyzed using the Taguchi performance evaluation framework and analysis of variance (ANOVA) to identify the parameters exerting the most significant influence on system energy performance and to determine the optimal configuration for maximum efficiency. Finally, an environmental assessment was conducted by estimating the reduction in carbon dioxide (CO₂) emissions resulting from the replacement of conventional fossil-fuel-based energy with geothermal energy. This analysis provided a quantitative measure of the environmental benefits and confirmed the sustainability potential of the sixteen-pile energy pile system for residential applications.

Table 1. Results of the energy pile system re-modeling at Zurich Airport

Calculated Parameter	Experimental Value	Modeled Value	Unit	Percentage Difference
Maximum heat extraction rate of the pile	72	70	W/m	2.7%
Annual energy extracted from the pile	183	177	kWh/m	3.2%
Annual energy injected into the pile	74	72	kWh/m	2.7%
Heat transfer rate to the ground	33	35	W/m	6.06%
Fraction of energy transferred to the ground relative to extracted energy	40.4	40.6	—	0.50%
Cooling demand coverage percentage	89	89	%	0%
Heating demand coverage percentage	78	79	%	1.2%
System coefficient of performance (COP)	4.8	4.9	-	2.08%

3.2. Case Study Building

The case study focuses on an eight-story residential complex located in the Saadat Abad district of Tehran, encompassing a total conditioned floor area of approximately 2,176 m². Figure 2 illustrates the typical floor plan and the architectural façade of the studied building.

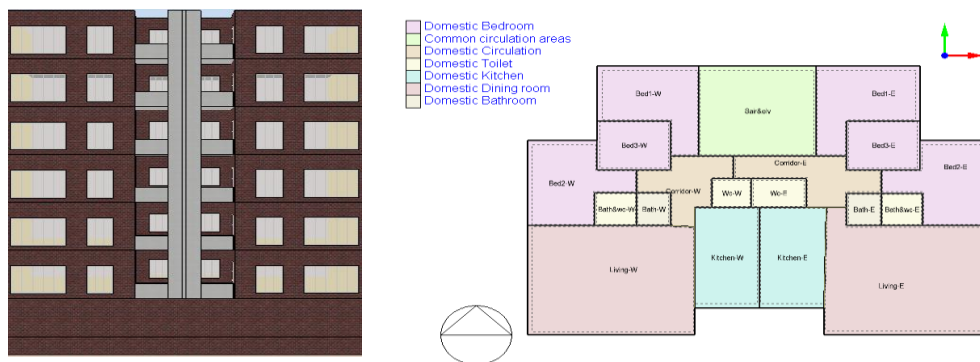


Fig. 2. Right: Typical floor plan; Left: Building elevation modeled in Design Builder.

The thermal performance of the building was simulated using *Design Builder* to evaluate its annual and peak heating and cooling demands under the prevailing climatic conditions. The simulation estimated annual heating and cooling energy requirements of 180.24 MWh and 26.22 MWh, respectively, with corresponding peak loads of 78.4 kW for heating and 69 kW for cooling. Comparison between the simulated results and the actual utility data revealed strong agreement, with deviations remaining below 7 %, thereby confirming the reliability and accuracy of the developed building energy model. To satisfy the identified thermal demands, a ground source heat pump (GSHP) system was selected and incorporated into the design configuration. Furthermore, the thermal properties of the local subsurface materials were integrated into the *PileSim 2* simulations to ensure a realistic representation of ground heat exchange performance. Table 2 summarizes the principal specifications of the GSHP unit employed in the analysis.

Table 2. Characteristics of the selected GSHP

Parameters	Values	Units
Heating Capacity	98	KW
Cooling Capacity	88	KW
Input electrical power of the compressor	16.9	KW
Coefficient of performance	4.45	-
Refrigerant	R134a	-
Heat carrier fluid	Water (70%) and ethylene glycol (30%) solution	-

3.3 Analytical Framework

To enhance the thermal performance of the 16-pile in energy piles system, an optimization framework based on the Taguchi design method was adopted. Three key design variables, pile depth, pile diameter, and heat-exchange pipe diameter, were selected as the primary factors governing system behavior. As summarized in Table 3, each factor was examined at three discrete levels, and an L9 orthogonal array was employed to construct the experimental design. This resulted in nine representative simulation scenarios, which were modeled using PileSim 2. The adopted framework enabled a systematic assessment of the sensitivity of the building's heating and cooling energy demands to variations in the selected geometric parameters. The simulation outputs were subsequently analyzed using Analysis of Variance (ANOVA) to quantify the relative contribution of each design factor to the overall energy performance of the system. This statistical evaluation provided a rigorous basis for identifying the most influential parameters and determining the optimal configuration that maximizes the thermal efficiency of the energy pile system. In accordance with the defined scope of this study, a preliminary estimation of carbon emission reduction was performed only for the optimal configuration. The estimation was based on emission factors of 0.203 kg CO₂/kWh for natural gas and 0.277 kg CO₂/kWh for electricity, as reported in Reference [17]. This calculation was intended to provide a comparative indicator of the potential reduction in greenhouse gas emissions associated with the optimized design, and the resulting values should be interpreted in light of the methodological simplifications adopted, rather than as outcomes of a full life-cycle carbon assessment.

Table 3. Parameters and levels used in this study for energy pile system

Parameters	Level 1	Level 2	Level 3	Units
Pile depth	15	20	25	m
Pile diameter	0.6	0.8	1	m
Tube diameter	25	50	100	mm

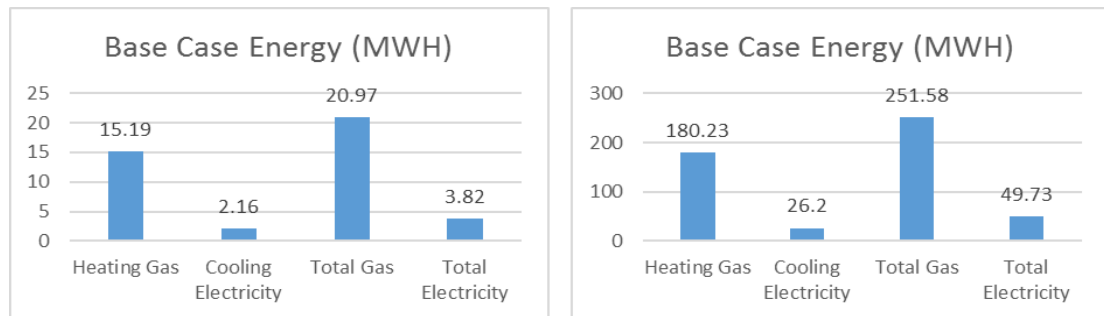
4. RESULTS

In this study, the performance of the energy pile system designed for the case-study building was evaluated through numerical modeling and optimization, using specialized simulation tools in conjunction with the Taguchi experimental design method. The reliability of the thermal simulations was first assessed by validating the model against available experimental data. The comparison showed a 6.06% deviation in the heat transfer rate, whereas the predicted cooling capacity matched the reference data with no observable error, indicating that the simulation framework provides acceptable accuracy. Subsequently, a detailed building energy model was developed in Design Builder to estimate the annual heating and cooling demands of the residential complex. The simulated results were compared with the actual electricity and natural gas consumption derived from utility bills. The annual discrepancy between simulated and measured electricity consumption was approximately 6%, while the difference for natural gas consumption was about 7%, confirming that the calibrated model can reliably represent the building's operational energy performance. The main outcomes of the baseline building simulation are summarized in Table 4, and the comparison between simulated and measured energy consumption is presented in Figure 3.

Table 4. presents the simulation results for the baseline building energy performance.

Parameter	Simulated Value (MWh)	Bills Value (MWh)	Error (%)
Annual heating energy consumption (West unit)	15.17		
Annual cooling energy consumption (West unit)	2.163		
Annual total gas consumption (West unit)	20.97	22.55	7%
Annual total electricity consumption (West unit)	3.822	4.082	6%
Annual heating energy consumption (Total building)	180.24		
Annual cooling energy consumption (Total building)	26.22		
Annual gas consumption (Total building)	251.59		
Annual electricity consumption (Total building)	49.74		
Building heating energy demand per year	102.9		
Building cooling energy demand per year	82.5		

The figure illustrates the energy simulation results for the western residential unit and the entire building. According to the simulation outcomes, the annual heating and cooling energy consumption of the western unit were estimated to be 15.169 MWh and 2.163 MWh, respectively. For the entire building, the annual heating and cooling energy consumption were calculated as 180.24 MWh and 26.22 MWh, respectively. The total annual natural gas and electricity consumption of the building were determined to be 251.59 MWh and 49.74 MWh, respectively. In addition, the simulation results indicated that the building's annual heating and cooling energy demands were approximately 102.9 MWh and 82.5 MWh, respectively. These values serve as the baseline reference for assessing the performance improvement of the proposed energy pile system in the subsequent optimization analyses.

**Fig. 3.** Energy simulation results from left to right: (a) western unit, and (b) entire building.

To comprehensively explore the design space of the 16-pile in energy piles system, characterized by an average pile spacing of 5.5 m, a Taguchi design matrix was constructed using Qualitek-4 software. Three critical geometric design variables, pile depth, pile diameter, and heat exchange pipe diameter, were designated as control factors, each defined at three distinct levels. Utilizing these parameters, Qualitek-4 generated nine unique design configurations, which subsequently formed the experimental matrix for all forthcoming simulations. These specific configurations are meticulously detailed in Table 5.

Table 5. Energy pile system configurations defined by Qualitek-4.

state	Pile depth (m)	Pile diameter (m)	Pipe diameter (mm)
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state1	15	0.6	25
State2	15	0.8	50
State3	15	1	100
State4	20	0.6	50
State5	20	0.8	100
State6	20	1	25
State7	25	0.6	100
State8	25	0.8	25
State9	25	1	50

Following the development of the experimental design matrix, all nine configurations were subjected to numerical analysis in PileSim 2 for the 16-pile in energy piles system. In each simulation, only the three Taguchi control factors, pile depth, pile diameter, and heat exchange pipe diameter, were varied, while all other boundary conditions and operational parameters were held constant to ensure a consistent and unbiased comparison among cases. The ground source heat pump (GSHP) operating conditions were uniformly applied in all simulations, based on the specifications previously reported in Table 2. The principal simulation assumptions and input parameters implemented in PileSim 2 are summarized in Table 6. These include the thermo-physical properties of the surrounding soil, basement ventilation rates and envelope characteristics, as well as subfloor structural and insulation details. All auxiliary parameters, namely ACH, UCELBU, HINSUL, and HMAGCO, were calculated using the formulations provided in the PileSim user manual, in combination with output data extracted from the Design Builder building energy model. A 50-year simulation period was adopted to account for the long-term thermal interaction between the energy piles and the surrounding ground.

Table 6. Key input data used for PileSim-2 simulations

Assumption / Description	Value	Unit	Reference
Thermal conductivity of soil	3	(W/M-K)	18
Volumetric heat capacity of soil	2.4	(MJ/M ³ K)	
Ground temperature at 8 m depth	1.5	c	18
Air change rate (ACH – cellar)	0.12	n	
Heat transfer coefficient of the cellar (Ucelbu-Cellar)	0.3	(W/M ² K)	
Thickness of basement floor insulation (H_insul)	16.5	cm	
Thickness of basement floor concrete (Hmagco)	11.5	cm	
Length of horizontal pipes (L_COEPE)	80	cm	
Simulation period	50	year	

The simulation outcomes obtained from PileSim 2 for the nine Taguchi design states of the 16-pile configuration with a spacing of 5.5 m are presented in Table 7. For each design scenario, the model provides the proportion of heating and cooling loads supplied by the energy piles, the required auxiliary (backup) heating and cooling energy, the total auxiliary energy demand, the corresponding heating and cooling coverage ratios, and the overall system coefficient of performance (COP).

Table 7. PileSim 2 simulation results for 16 energy piles with 5.5 m average spacing

state	Heating fraction(kwh)	cooling fraction(kwh)	Auxiliary heating(kwh)	Auxiliary cooling(kwh)	heating %	Cooling %	cop
state1	67,400	20,500	35,500	62,000	66%	25%	4
State2	71,300	23,200	31,600	59,300	69%	28%	4
State3	76,900	29,900	26,000	52,600	75%	36%	4.1
State4	83,300	30,600	19,600	51,900	81%	37%	4.1
State5	89,100	37,400	13,800	45,100	87 %	45 %	4.1
State6	88,400	33,100	14,500	49,400	86 %	40%	4.1
State7	96,000	41,700	6,900	40,800	93 %	51 %	4.2

State8	96,100	38,100	6,900	44,400	93 %	46 %	4.2
State9	98,900	42,400	4,100	40,100	96 %	51 %	4.3

A clear improvement in system performance is observed with increasing pile depth and diameter, particularly in the higher-capacity configurations. For instance, State 1 provides approximately 67,400 kWh of heating and 20,500 kWh of cooling, corresponding to about 66 % coverage of the heating demand and 25 % of the cooling demand. In contrast, State 9, characterized by the largest geometric dimensions (25 m pile depth and 1.0 m diameter) combined with a 50 mm heat exchange pipe, delivers nearly 98,900 kWh of heating and 42,400 kWh of cooling. This configuration achieves approximately 96 % coverage of the heating load and 51 % coverage of the cooling load. The intermediate configurations (States 2–8) demonstrate a progressive decrease in auxiliary energy requirements alongside a gradual increase in the proportion of heating and cooling supplied by the ground-coupled system. Correspondingly, the system coefficient of performance (COP) improves from the baseline case toward the best-performing configuration. Overall, the results derived from the Taguchi design matrix clearly indicate that appropriate selection of pile depth, pile diameter, and heat exchange pipe diameter can significantly enhance the contribution of energy piles to meeting building thermal loads. Such improvements reduce dependence on auxiliary heating and cooling systems and contribute to higher overall energy efficiency and improved environmental performance of the Energy-pile system.

These findings provide the quantitative foundation for the subsequent sensitivity assessment using analysis of variance (ANOVA) and for identifying the optimal configuration within the Taguchi design framework. To evaluate the relative influence of each design parameter on the system's thermal performance, the simulation outputs obtained from PileSim 2 for the Taguchi test states were imported into Qualitek 4, where a comprehensive analysis of variance (ANOVA) was conducted. This analysis enabled a quantitative assessment of the effects of the three primary parameters, pile depth, pile diameter, and heat exchange pipe diameter, on the heating and cooling supply as well as on the associated environmental indicators. The initial sensitivity analysis results are summarized in Table 8, where the parameter ranking based on the F-ratio highlights the most influential design variables.

Table 8. Sensitivity Analysis of the Energy Pile System

Level	Pile depth	Pile diameter	Pipe diameter
Factor ranking to maximize heating energy supply using the larger-is-better criterion			
1	71.33	82	83.66
2	86.66	85.33	84
3	96.66	87.33	87
F-RATIO	4389.06	195.702	90.85
Ranking	1	2	3
Factor ranking to maximize cooling energy supply using the larger-is-better criterion			
1	24	33.30	33.30
2	33.33	32.66	31.66
3	40.33	34.66	35.66
F-RATIO	453.42	31.76	52.02
Ranking	1	3	2
Factor ranking to maximize heating and cooling energy supply using the larger-is-better criterion			
1	95.66	112.33	114
2	120	118	116
3	137.33	122.66	123
F-RATIO	3908.93	238.92	199.26
Ranking	1	2	3

As reported in Table 8, for all “larger-is-better” performance criteria, namely heating supply, cooling supply, and combined thermal contribution, pile depth consistently exhibits the highest F-ratio, highlighting its dominant influence on overall system performance. Pile diameter is identified as the second most influential factor, whereas

pipe diameter has the smallest impact on performance variability. This consistent ranking across all evaluated criteria emphasizes the governing role of pile depth in controlling the long-term heat exchange between the foundation system and the surrounding ground. Subsequently, ANOVA was conducted for four independent optimization objectives: maximizing heating output, maximizing cooling output, and maximizing total thermal supply. The associated P-values for each objective are summarized in Table 9.

Table 9. P-values (%) for energy pile system parameters across various objectives.

Objective	Pile depth	Pile diameter	Pipe diameter	OTHER/ERROR
Increasing heating energy supply	93.83	4.16	1.92	0.09
Increasing cooling energy supply	84.06	5.71	9.48	0.75
Increasing heating and cooling energy supply	89.87	5.47	4.56	0.94

The very high proportion of variance associated with pile depth, typically exceeding 80%, confirms its overwhelming influence across all performance metrics, whereas pile diameter and pipe diameter account for substantially smaller fractions of the total variance. Based on these outcomes, the optimal levels of the design parameters were identified, and the corresponding results are summarized in Table 10.

Table 10. Optimal design parameters for different optimization objectives of the energy pile system

Optimization Objective	Pile Depth (m)	Pile Diameter (m)	Heat Exchanger Pipe Diameter (mm)
Maximization heating of energy supply	25	1.0	100
Maximization of cooling energy supply	25	1.0	100
Maximization of combined heating and cooling energy supply	25	1.0	100

As shown, all three optimization objectives, heating, cooling, and combined thermal performance, converge to the same design configuration, comprising a pile depth of 25 m, a pile diameter of 1 m, and a pipe diameter of 100 mm. The consistency of the optimal levels across multiple independent objectives highlights the robustness and reliability of this configuration for practical system implementation. To validate the selected optimal design, the identified configuration, consisting of 16 piles, each with a depth of 25 m and equipped with 100 mm pipes, was re-simulated in PileSim 2 under two operational modes, namely Forward and Return. The detailed simulation results are presented in Table 11.

Table 11. Performance indicators of the optimized energy pile system simulated in PILESIM2

Parameter	Forward Case	Return Case	Unit
Maximum heat extraction rate	113	116	W/m
Annual energy extracted from pile	189	194	kWh/m
Annual energy injected into pile	106	126	kWh/m
Heat transfer rate to ground	111	90	W/m
Ratio of energy transferred to ground to extracted energy	56	65	%
Heating demand coverage	96	98	%
Cooling demand coverage	51	61	%

According to the results summarized in Table 11, the Forward operating mode supplies approximately 96% of the annual heating demand and 51% of the cooling demand, with a maximum heat extraction rate of 113 W/m. Under the Return mode, system performance improves further, achieving 98% heating coverage and 61% cooling coverage, accompanied by a peak heat extraction rate of 116 W/m. In addition, based on the CO₂ emission factors reported in Reference [17], a simplified estimation of annual carbon emission reduction was performed for the optimal configuration. Based on the obtained results, the annual CO₂ emissions are reduced by approximately 30,390 and 30,650 kg per year in the Forward and Return modes, respectively, compared to the baseline case. These values

provide a comparative indication of the potential environmental benefit associated with reduced auxiliary energy consumption and should be interpreted within the limitations of the adopted simplified approach. Overall, the integrated Taguchi–ANOVA optimization framework indicates that the configuration consisting of a 25 m pile depth, 1 m pile diameter, and 100 mm pipe diameter for the 16-pile energy pile system achieves the highest heating and cooling performance among the investigated configurations. This optimal configuration substantially reduces the reliance on auxiliary heating and cooling systems for the studied residential building in Tehran.

5. CONCLUSION

This study evaluated the potential of an energy pile system to meet the heating and cooling demands of a residential building in Tehran. The numerical model developed in PileSim 2 was first validated against reference data, showing deviations below 7%, which confirms the reliability of the simulation framework. A parametric analysis was then conducted using the Taguchi method and ANOVA to assess the influence of key design parameters. The results identified pile depth as the most influential parameter affecting thermal performance, with a significantly greater contribution than pile diameter and pipe diameter. The optimal configuration consisted of 16 energy piles with a depth of 25 m, pile diameter of 1 m, and pipe diameter of 100 mm. Under these conditions, the system was able to meet approximately 97% of the annual heating demand and 56% of the annual cooling demand, substantially reducing the need for auxiliary systems. A simplified estimation of carbon emission reduction was also performed for the optimal configuration based on emission factors reported in the literature. The results indicate a potential reduction in CO₂ emissions associated with decreased auxiliary energy consumption. Overall, the findings highlight that properly designed energy pile systems can significantly enhance building energy efficiency and reduce conventional energy demand in residential buildings, particularly in dense urban areas with climatic conditions similar to Tehran.

Declaration

During the preparation of this work, the authors used [ChatGPT (OpenAI)] to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

Acknowledgments

We would like to express our gratitude to all individuals who contributed to this project.

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 paper.

Funding

This research received no specific grant from any funding agency, commercial, or not-for-profit sectors.

Ethics Considerations

Not applicable. This study did not involve human participants, animals or personal data.

Data Availability

The simulation input data and results supporting the findings of this study are available from the corresponding author upon reasonable request.

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