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Challenges and prospects

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Research Paper

A critical assessment and summary on the low carbon energy pile technologies based on the life-cycle perspective: Challenges and prospects

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ABSTRACT

Energy piles, a technology integrating the heat exchange component within building pile foundations for shallow geothermal energy utilization, have proven economically efficient. They outperform conventional ground source heat pumps by mitigating additional borehole costs and space requirements. This paper systematically examines low-carbon considerations and optimization measures throughout the planning, design, construction, and operation stages of energy piles, considering the entire lifecycle. Furthermore, this paper discusses potential challenges associated with decarbonizing energy piles, offering solutions based on case studies and environmental impact assessments. Through a comprehensive critical review and analysis of existing knowledge, this paper presents a systematic theory and methodology for optimal decarbonization of energy piles, serving as a valuable resource for building practitioners and researchers in this field. The findings not only contribute to a solid theoretical foundation but also provide technical support for the advancement and application of energy pile systems.

1. Introduction

In recent years, the global climate crisis has gained increasing prominence, primarily attributed to the extensive burning of fossil fuels and the resultant emission of greenhouse gases [1,2,155]. Reports indicate that achieving the Paris Agreement goal of limiting global warming to below 2 °C by 2030 requires a system-wide transformation, necessitating a 30 % reduction in emissions [3]. The Global Status Report for Buildings and Construction emphasizes the significant role of the building sector [153,154]], which accounted for 34 % of total final energy consumption and 37 % of global operational energy and process-related CO_2 emissions in 2021 [4]. In China, the building and construction sector alone contributed to 50.6 % of CO_2 emissions [5]. Therefore, it is imperative to reduce energy consumption and greenhouse gas emissions within the building sector to effectively work towards the carbon neutrality target [6,7].

In addressing this challenge, numerous scholars have directed their focus towards harnessing geothermal energy—a clean and renewable energy source that presents a viable alternative to fossil fuels, particularly in building heating, ventilation, and air conditioning (HVAC) systems [8–10]. Within the realm of shallow geothermal energy utilization, energy piles have emerged as a focal point of interest among scholars. Energy pile constitutes a closed-loop ground source heat pump with three primary components: an earth connection subsystem, a heat pump subsystem, and a heat distribution subsystem [11]. The heat exchange pipes of energy piles are intricately embedded within the building's foundation piles, strategically positioned at a depth where soil temperature remains relatively stable. This symbiotic arrangement between foundation piles and heat exchange pipes forms a geothermal exchanger facilitating heat exchange with the surrounding soil [12,13]. Compared to traditional HVAC technology, energy piles exhibit both environmental and economic advantages throughout their life cycle, despite initial installation costs. Their diminished reliance on conventional energy sources and high energy efficiency contribute significantly to the reduction of CO_2 emissions [14–16]. Furthermore, energy piles offer broader applicability compared to other clean energy technologies, such as solar, wind, and tidal energy, given that shallow geothermal energy is geographically unrestricted. The concrete piles utilized in energy piles boast high thermal conductivity and heat storage

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Nomenclature

Abbreviations

CFA	Continuous flight auger
COP	Coefficient of performance
GA	Genetic algorithm
GAHE	Ground-air heat exchanger
GHE	Ground heat exchanger
MOO	Multi-objective optimization
RSM	Response surface methodology
HAVC	Heating, ventilation, and air conditioning
LCA	Life cycle assessment
MOO	Multi-objective optimization
NSGA-II	Non-dominated Sorting Genetic Algorithm II
PCMs	Phase change materials
PHC	Prestressed high-intensity concrete
SiC	Silicon carbide
SOO	Single-objective optimization
TPT	Thermal performance test
WSHP	Water source heat pump

Symbols

d	Diameter
k	Thermal conductivity
f_e	Electricity-related CO_2 emission factor
E_{elec}	Electricity consumption
f_n	Natural gas-related CO_2 emission factor
E_{gas}	Natural gas consumption
Q	Heat exchange rate
c_p	Specific heat capacity
v	Velocity
ρ	Density
T	Temperature

capabilities, enhancing heat transfer efficiency between the pile and the surrounding soil in contrast to conventional borehole heat exchangers [17]. In addition, the integration of heat exchanger pipes within the pile foundation eliminates the necessity for additional boreholes, thereby reducing drilling costs and minimizing underground space consumption [18].

As a competitive geothermal heat exchanger technology, energy piles have been the subject of extensive research, covering the development of heat transfer models [19], sizing methods [20,21], and evaluations of technical, environmental, and economic feasibility [22]. These research endeavors have played a pivotal role in improving the energy efficiency of both the energy pile system and the buildings they serve. Laboratory, field, and numerical studies have documented these advancements [23]. Furthermore, investigations into the decarbonization potential of energy piles have been conducted. For instance, Han et al. [24] discovered that energy piles can achieve an average reduction in carbon emissions ranging from 25 to 36 % across different climate zones in eight cities. In a study conducted by Akrouch et al. [16] in Texas, USA, primarily under cooling weather conditions, and the implementation of an energy pile system resulted in a noteworthy reduction of electricity consumption by 5573MWh and carbon emissions by 3932 metric tons over 30 years. These studies underscore the significant advantages of energy piles in reducing carbon emissions through the utilization of geothermal energy and the enhancement of energy efficiency.

Based on above-mentioned literature review, several research gaps can be identified: 1) Existing research lacks a systematic summary of the carbon reduction effect of energy piles from the life-cycle perspective. 2) Existing studies on the decarbonization potential of energy piles primarily focus on reducing operational carbon emissions, neglecting the embodied carbon emissions associated with the construction stage and building materials. 3) The challenges and future research directions for maximizing the decarbonization potential of energy piles have not been adequately discussed in the existing studies.

This study aims to address these gaps by providing a comprehensive analysis of decarbonization considerations for energy piles at different life cycle stages. Relevant literature on their design, construction, operation, and comprehensive evaluation will be reviewed. Additionally, the study will outline potential challenges and barriers in using energy piles for carbon reduction and suggest future research directions to further minimize their carbon footprint. The following sections are organized as follows: Section 2 introduces the physical configuration of energy piles and discusses the advantages and disadvantages of each type. Section 3 and Section 4 summarize the decarbonization considerations for the design and construction stage, while Section 5 analyzes carbon reduction methods for the operation and monitoring stage. Section 6 provides an overview of the evaluation of the decarbonization potential for energy piles. Finally, Section 7 discusses the challenges and future research areas. A conclusion is presented in Section 8. This study will serve as a guideline for the future design, construction, operation, and evaluation of energy piles, offering technical support for achieving carbon neutrality in the building industry.

2. Common classifications and key impact parameters

2.1. Common classification

Energy piles and conventional ground source heat pumps are distinguished primarily by their underground energy structure. Energy piles can be categorized into different types based on the characteristics of the underground structure, considering the pile type and the configuration of pipes within the pile. Common energy pile types encompass cast-in-place reinforced concrete piles [18,25–27], steel piles [28–31], and precast reinforced concrete piles [32,33]. The configuration of pipes within energy piles varies, including single U-shaped, W-shaped, double U-shaped, triple U-shaped, helical [34,35]. U-shaped and W-shaped energy piles have pipes bent accordingly, while helical energy piles feature a spiral-shaped pipe. In terms of the connection forms of pipes, they can be divided into parallel and series types [36]. A visual representation of these structures can be seen in Fig. 1. The selection of the appropriate energy pile type depends on the specific geological conditions, load requirements, construction costs, and other factors.

The various forms of pipes directly affect the thermal performance, economic viability, and construction feasibility of energy piles [37–40]. Park et al. [33] proposed that the triple U-shaped energy pile had a better performance than the W-shaped energy pile. Mehrizi et al. [37] conducted a cooling performance comparison among three energy pile types (e.g., single U-shaped, W-shaped, and W-shaped-all round) and concluded that W-shaped-all round energy pile exhibited the best heat transfer efficiency. Gao et al. [38] evaluated the heat transfer efficiency of different types of cast-in-place concrete energy piles, determining that triple U-shaped energy piles were the most efficient, while W-shaped energy piles excelled at moderate media flow rates. Zarrella et al. [39] analyzed a model and found that, under the same pile geometry conditions and with identical pile and pipe materials, the spiral-shaped pipe demonstrated superior thermal performance compared to the triple U-shaped pipe. Khandouzi et al. [40] simulated the performance of single U-shaped, W-shaped, spiral-shaped, and 6U-shaped heat exchangers at different depths, revealing that the 6U-shaped configuration had the highest efficiency, followed by helical-shaped, W-shaped, and single U-

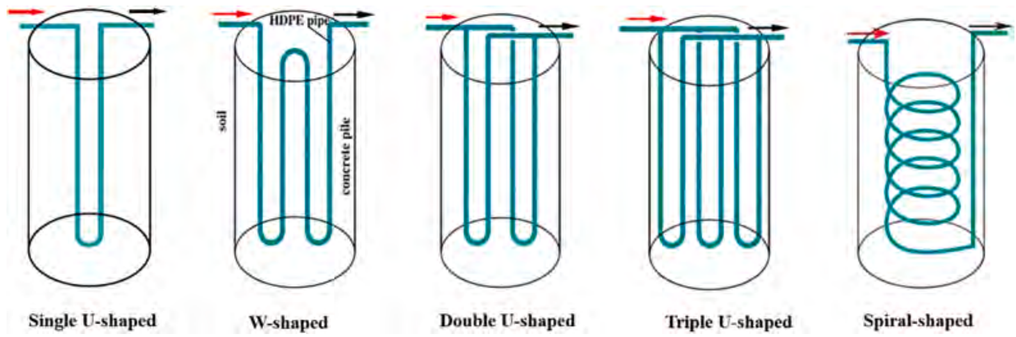

Fig. 1. Schematic diagram of different types of pipe configuration in energy pile [34,35].

shaped.

Yoon et al. [41] conducted a thermal performance test (TPT) comparing prestressed high-intensity concrete (PHC) energy piles with W-shaped and spiral-shaped pipes. They found that the heat flux of the spiral-shaped energy pile is higher. However, the construction cost of W-shaped energy piles is approximately three times lower due to the more expensive unit price and longer required length of spiral-shaped pipes. Meanwhile, Luo et al. [34] assessed the cost-benefits ratio of four types of pipe (e.g., double U-shaped, spiral-shaped, double W-shaped, and triple U-shaped) based on the heating and cooling needs of buildings and energy prices, and concluded that the triple U-shaped ground heat exchanger (GHE) has the highest economic performance, followed by double U-shaped, spiral-shaped, and double-W-shaped. However, in practical engineering, the absolute value of the heat output is often more crucial than cost considerations. Additionally, the construction feasibility of different pipe configurations also varies. For example, multi-U-shaped pipes require more complex installation due to multiple inlet and outlet ports, while the installation of spiral-shaped pipes typically requires more manpower [25,26].

The observed variance in heat transfer efficiency among different pipe types primarily stems from differences in the contact area between the pipe and the concrete [42–45]. As the contact area increases, the heat transfer efficiency increases. Considering the thermal performance and construction feasibility, the potential application of spiral-shaped pipes appears promising. Nevertheless, the selection of pipe configuration should also consider economic factors and construction constraints. Further research is essential to optimize the design and performance of energy piles with different pipe configurations.

2.2. Key influencing factors

Numerous factors influencing the thermal performance of energy piles fall into distinct categories: environmental, design, construction, and operating factors, as outlined in Table 1.

Environmental factors are essential considerations for any project. While these factors, such as site climatic conditions [46–49], thermal properties of the surrounding soil [50–52], groundwater condition (e.g., groundwater velocity, groundwater seepage, and groundwater level. [53–58]), cannot be optimized, they must be carefully taken into account to ensure a reasonable design. In contrast, design factors offer optimization opportunities during the design process. This includes adjusting the volumetric flow rate of the heat transfer fluid and considering geometric factors like pile length, diameter, pipe number, pipe length, and diameter.

Construction factors mainly include the construction method during the construction process and the selection of materials. The thermal conductivity (including thermal conductivity of heat transfer fluid, and thermal conductivity of pile material) and other thermophysical properties of materials (e.g., latent heat) have an impact on the operational efficiency of energy piles.

Operating factors involve adjustments made during operation to achieve changes in system performance. Scholars focus on studying operation patterns, considering both temporal and spatial dimensions. Current research emphasizes the impact of intermittent operation temporally, while spatially, discussions involve grouping energy piles and zoning operation under various operating conditions.

Table 1
Summary of factors affecting the thermal performance of energy piles.

Environmental factors	Site climatic conditions [46–49] Thermal properties of the surrounding soil [50–52] Groundwater condition [53–58]	
Design factors	Geometric factors	Pile length [46,59,60] Pile diameter [46,61,62] Pipe number [63–65] Pipe length [45,66] Pipe diameter [46,67,68] Pile group arrangement [58,69,70]
Construction factors	Construction method [71,72]	
	Material factors	Thermal conductivity of heat transfer fluid [61,73–75] Thermal conductivity of pile material [62,76,77] Thermal conductivity of pipe material [78,79] Other thermophysical properties [80,81]
Operating factors	Operation patterns	Intermittent operation [82–85] Zoning operation [86]

3. Decarbonization considerations in design stage

3.1. Optimize design method

In the energy pile optimization process, the pivotal task involves defining objectives, variables, and optimization methods within specific constraints [87]. Design optimization can be categorized into single-objective optimization (SOO) and multi-objective optimization (MOO), depending on the number of optimization objectives [19]. The common optimization objectives can be summarized according to the “4E” criteria (i.e., energy criteria, exergy criteria, economy criteria, and environment criteria) [88]. This section will assess the optimization of energy pile design from a decarbonization perspective. Specifically, it will review optimization strategies with “energy criteria” and “environmental criteria” as primary design objectives, examining both SOO and MOO perspectives.

3.1.1. Single-objective optimization

Alberdi-Pagola et al. [70] proposed an optimization strategy based on the desirability function approach to maximize the pile spacing through a local optimization algorithm. This strategy leads to a reduction in the number of piles required for the pile group to meet the thermal load demand of the building. Ahmed et al. [79,89] identified nine design parameters and analyzed their significance using fractional factorial uniform design of experiments. Subsequently, Haridy et al. [90] refined the parameter significance analysis based on this, employing response surface methodology (RSM) to optimize cooling-dominated energy piles. They determined the significance of each design parameter by analyzing the effect of eight design parameters on the thermal conductivity of the energy pile. Cecinato and Loveridge [61] used Taguchi analysis to analyze the key parameters of energy piles and optimize the design of energy piles by determining the relative importance of each parameter. Nazmabadi et al. [91] proposed a thermal recovery system that incorporates an open-loop ground-air heat exchanger (GAHE) pipe in the spiral-shaped energy pile. They combined genetic algorithms (GA) with response surface methods to optimize this system. In the optimization process, they used spiral pitch, pipe diameter, GAHE diameter and GAHE air inlet velocity as the main design parameters to optimize the maximum cooling load of per unit depth of energy pile provided by the overall system.

Numerous studies optimize design by simulating operational performance under different sets of design parameters. Bezyan et al. [92] compared the heat transfer efficiency of spiral energy piles with pitch of 0.2 m, 0.4 m, and 0.6 m, respectively. Carotenuto et al. [62] investigated the heat transfer performance of energy piles through numerical simulations using three geometry configurations of probes (i.e., double U-shaped, triple U-shaped probes and spiral coils) developed with COMSOL Multiphysics and their performance was compared under different physical properties of the pile, geometrical characteristics of probes and fluid flow rate. After the traditional method of improving the heat transfer efficiency of energy piles by optimizing their geometric design configuration reached a bottleneck, some innovative optimizations were proposed. To improve the thermal conductivity of concrete, graphite was added to the concrete. Through laboratory testing and numerical simulations, Li et al. [93] compared the thermal efficiency of concrete energy piles containing different contents of graphite. Elkezza et al. [94] added different proportions of graphite powder into concrete and compared the thermal conductivity and the compressive strength of graphite-concrete with normal concrete. It was found both the thermal conductivity and the compressive strength of graphite-concrete were significantly improved. In addition to that, in Ref. [95–100], various novel pipe forms and their parameters are investigated to improve the thermal performance of energy piles. However, as no specific optimization method is employed, these optimizations often do not consider all possible solutions, and the outcomes may not be optimal.

3.1.2. Multi -objective optimization

As previously mentioned, MOO involves multiple optimization objectives. Based on the findings of Ref. [93], the possible effect on the strength of concrete with the addition of graphite was considered by Li et al. [101]. They made another attempt to add silicon carbide (SiC) to the concrete. They found that the SiC concrete not only increased in thermal conductivity but also in strength as the content of SiC increased. Meng et al. [102] developed an ontology-based decision support system for multi-optimal design of energy pile systems. The system prioritizes equipment cost, cost recovery period, CO_2 emission reduction and vertical loading capacity as the key design indicators. By using this system for multi-objective optimization design of cases, the authors finally obtained eight different optimized design solutions. Farajollahi et al. [67] analyzed the sensitivity of parameters in three-helix-shaped energy piles using response surface models, and then optimized the system using Non-dominated Sorting Genetic Algorithm II (NSGA-II).

While multi-objective optimization is not yet widely used in energy piles, its potential for integrating energy efficiency and environmental considerations through suitable optimization strategies is valuable for the decarbonization application of energy piles. More details of these SOO and MOO studies reviewed and the major findings obtained are summarized in Table 2.

3.2. Optimized influencing factors

The design stage holds substantial influence over the environmental impact of energy piles [104]. As the project progresses, the ability to impact environmental performance diminishes [105]. This is particularly true considering the challenges of altering the design of energy piles once the pile foundation begins to bear the load of the superstructure. Consequently, it is crucial to judiciously set key parameters during the design stage to enhance overall efficiency and minimize the carbon footprint of buildings. This section will outline the key parameters that affect the thermal performance of energy piles, offering the guidances for energy pile design.

3.2.1. Heat transfer fluid

Inside the pipe, the primary parameter affecting thermal performance is the heat transfer fluid. The heat transfer fluid circulates in the pipes to transfer heat between the ground and the heat pump system. Differences in the thermal conductivity and volumetric flow rate of the heat transfer fluid can have an impact on the thermal performance of the energy pile.

Common heat transfer fluids include pure water, water with antifreeze, or saline solutions [106]. Antifreeze options include ethylene glycol or propylene glycol. Ethylene glycol boasts advantages such as a lower price, high thermal conductivity, and low viscosity compared to propylene glycol. On the other hand, propylene glycol is non-hazardous [107]. Antifreeze is added to prevent fluid freezing during heat transfer. However, it's crucial to consider that increasing the antifreeze content raises fluid viscosity, potentially reducing heat transfer efficiency [108]. Therefore, selecting an appropriate antifreeze ratio is essential based on actual requirements. Currently, innovative approaches to heat transfer fluids have been proposed [73–75]. Researchers add nanofluids into heat transfer fluids to enhance their heat transfer properties.

3.2.2. Pipe diameter and the velocity of heat transfer fluid

The volumetric flow rate of the fluid is regulated by the pipe diameter and fluid velocity combined [109]. Typically, even though pipes may have varying shapes, an increase in pipe diameter and fluid velocity leads to an elevation in the volumetric flow rate, as depicted in Fig. 2. The heat flux of pile increases with volumetric flow rate until a certain critical value is reached. It can be explained by the relationship between Reynolds number and Nusselt number [59]. However, the growth of heat flux is nonlinear [28,46]. A blind increase in flow rate can diminish the time available for heat exchange, eventually resulting in inadequate heat exchange between the fluid and the surrounding soil [67,101,102]. In addition, Ding et al. [46] also proposed that the optimal design volumetric flow rate of the heat transfer fluid is different in summer and winter. Therefore, determining a reasonable volumetric flow rate is essential to avoid insufficient heat exchange or low heat transfer rates.

3.2.3. Pipe number

In general, an increase in the number of pipes has demonstrated a substantial improvement to the heat exchange performance of the energy pile [63,64]. However, a higher number of pipes leads to a more pronounced temperature development in the pile, resulting in increased thermal interaction between pipes [65]. The benefits of the additional pipe are gradually diminishing [110]. There is a significant nonlinearity between the increase in the number of pipes and the increase in exchanged power, as shown in Fig. 3 [61,111].

3.2.4. Pipe length

For energy piles configured with U-shaped pipes, altering the length of the pipes is typically accomplished by adjusting the number of pipes, and the impact aligns with the aforementioned considerations. However, for energy piles configured with spiral-shaped pipe, increasing the

Table 2
Summary of the basic information reported in the studies considering SOO and MOO.

Ref.		Optimization objective	Optimization variables	Optimization technique	Main findings
[70]	SOO	minimum pile number	Pile spacing	Local optimization algorithm	By optimization, the number of energy piles required for the case in the literature can be reduced by 32 %.
[79]	SOO	thermal conductance	Number of tubes, Pile diameter, Tube diameter, Tube thickness, Tube location, Pile conductivity, Tube conductivity, Soil conductivity, Water flow rate	Fractional factorial uniform design	Energy piles exhibit larger steady-state thermal conductivity for larger number of tubes, tube diameter, tube spacing and pile thermal conductivity.
[90]	SOO	thermal performance of the energy pile	Number of tubes, Pile diameter, Inner tube diameter, Tube thickness, Pile thermal conductivity, Soil thermal conductivity, Tube thermal conductivity, Water velocity	RSM	Inner diameter of U-tubes, pile thermal conductivity and tube thermal conductivity have significant influence on the thermal conductivity of the pile. The increase in thermal conductivity of tube and pile, as well as the increase in inner diameter, can significantly increase the thermal conductivity of energy piles. Tube thickness and water velocity do not have little effect on the thermal conductivity of the pile. When the pile diameter of the energy pile is large, the increase in the number of pipes helps to improve the thermal conductivity.
[92]	SOO	heat transfer rate	Pitch sizes	N/A	Spiral-shaped energy pile with 0.4 m pitch size had higher efficiency in heat transfer rate than the pile with 0.2 m or 0.6 m pitch size.
[61]	SOO	energy efficiency	Pile diameter, Pile length, Concrete cover, Concrete thermal conductivity, Pipe number, Pipe diameter, fluid flow velocity.	Taguchi method	Total pipe surface area is the most important factor for energy efficiency. The flow rate of the heat transfer fluid has a small effect on the overall exchanged energy of the energy pile.
[91]	SOO	provided cooling load per unit depth of the energy pile	Spiral pitch, Pipe diameter, ground-air heat exchanger (GAHE) pipe diameter, GAHE air inlet velocity	RSM GA	The use of a recovery system can increase the maximum provided cooling load of the system by 50 %. The 15-year average annual COP of energy piles with double GAHE pipe and single GAHE pipe recovery systems is increased by 30 % and 16 %.
[62]	SOO	heat transfer rate	Concrete density, Concrete thermal conductivity, Pile diameter, Probe diameter, Fluid flow rate, Probe shape	N/A	The heat transfer performance increases with the increase of thermal conductivity. Spiral-shaped energy piles have better thermal performance than single-U-shaped, double-U shaped and triple-U shaped energy pile. Within a certain range, an increase in pile diameter or pipe diameter can lead to an increase in heat transfer rate.
[103]	SOO	exchanged power of energy micro-piles	Fluid velocity, Pipe thermal conductivity, Fluid thermal conductivity, Pile diameter, Pile length, Concrete thermal conductivity, Pipe diameter	Taguchi method	The design of energy micro-piles is different from the design of energy piles. the pipe diameter is a key factor in the design of energy micro-piles. Among the site factors, the extent of thermal insulation between the ground and the building is also very important, in addition to the ground thermal conductivity.
[93]	SOO	total thermal resistance	Graphite volumetric contents	N/A	Graphite can improve the heat transfer coefficient, with a graphite content preferably higher than 15 %.
[101]	MOO	thermal conductivity of concrete the strength of the concrete	SiC contents Graphite contents	N/A	Although the increase of graphite content can make concrete thermal conductivity increase, however, the strength of concrete will be significantly reduced. The average thermal conductivity reaches 2.92 W/(m·k) and the compressive strength of concrete is 28.7 MPa when the graphite content reaches 15 %, indicating a reduction of 29.8 % in strength (The compressive strength of block without graphite is 42.3 MPa). When the SiC content is 15 %, the thermal conductivity reached 2.47 W/ (m·k) and the compressive strength was increased by 6.8 %.
[67]	MOO	the ratio of the load provided to the load required by the building the system cost	Helix pitch, Helix diameter, Pipe diameter	RSM NSGA II	The helix pitch is the most key parameters influencing the thermal performance, followed by helix diameter and the pipe diameter.

length of pipe within a fixed pile length can also be achieved by narrowing the pitch. It's important to note that while narrowing the pitch enhances the exchanged power of the pile, it concurrently diminishes the heat flux of the pipe due to the adverse interactions between pipes [45,62,66], as illustrated in Fig. 4.

3.2.5. Pile length

Pile length exerts a substantial influence on the thermal performance of energy piles [59–61]. The exchanged power of the pile markedly increases with a longer pile length due to the expanded contact area. However, it's crucial to note that the thermal efficiency per unit area cannot be enhanced indefinitely, as depicted Fig. 5. Furthermore, the selection of pile length is more contingent on the load-bearing requirements of the pile than on the thermal properties.

3.2.6. Pile diameter

In general, larger pile diameters improves energy efficiency of energy piles [61]. This is because a larger diameter allows for a reasonable

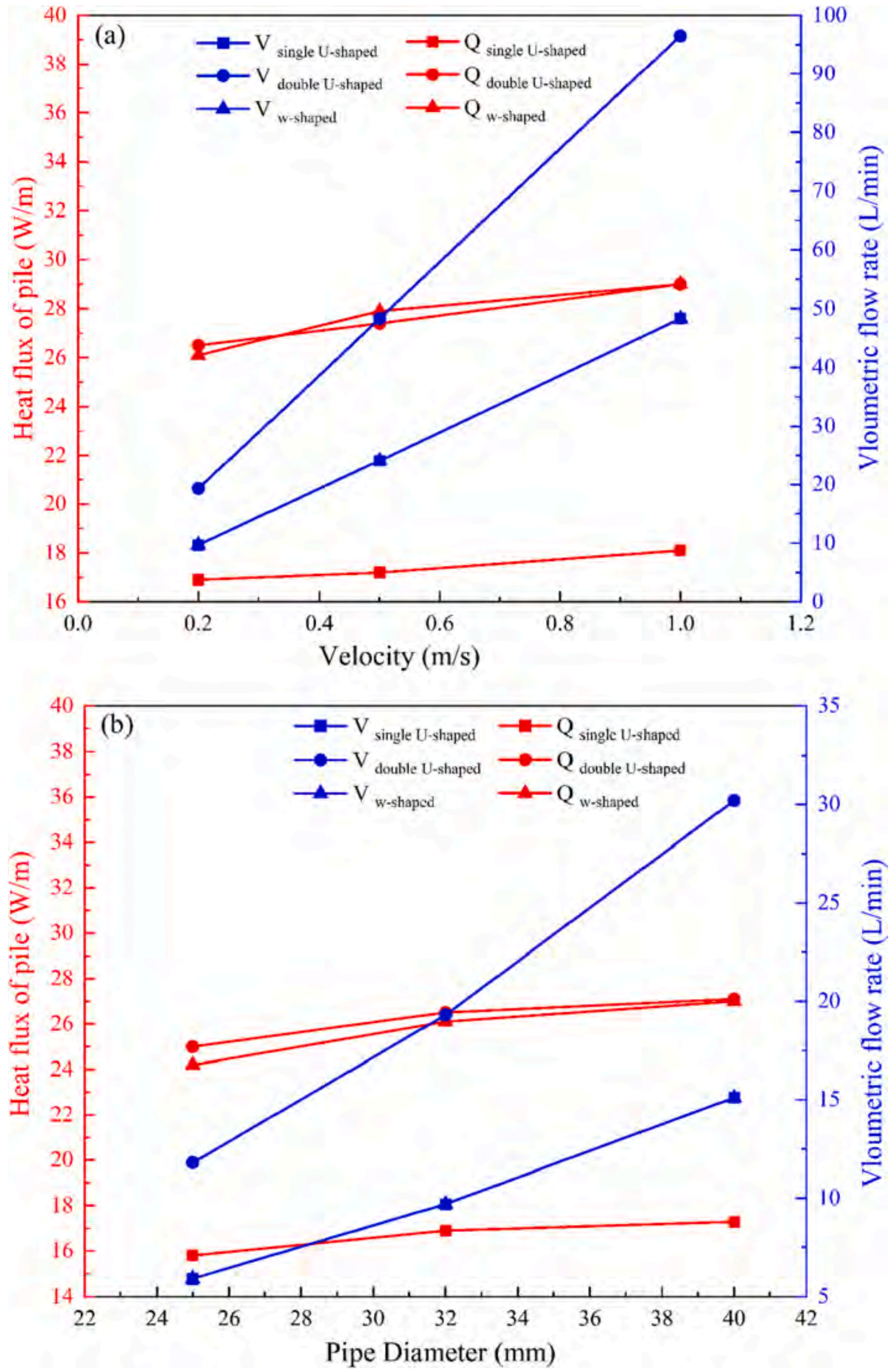

Fig. 2. The heat exchange rate and volumetric flow rate of the fluid: (a) for different fluid velocity [109]; (b) for different pipe diameters [109].

spacing of the internal pipes, and the mutual thermal interference between the pipes affects the overall efficiency of the energy pile [62], see Fig. 6 (a). In addition, a larger diameter also provides the possibility of placing more pipes in the same pile, resulting in the improvement of the efficiency of a single pile. Ding et al. [46] found that except for individual months, the maximum exchanged power increases with the increase of pile diameter, but the difference is not significant, as shown in Fig. 6 (b).

3.2.7. *Comprehensive analysis*

Currently, there is limited literature on the comprehensive analysis of various parameters of energy piles. Cecinato and Loveridge [61] conducted a thorough analysis of pile length, pile diameter, pipe diameter, number of pipes, heat transfer fluid flow rate, concrete thermal conductivity, and thickness of concrete cover and ranked the importance of these parameters, see Fig. 7 (a). Ahmed et al. [79] defined nine factors: number of pipes (n), pile diameter (d_p), pipe diameter (d_i), pipe thickness (T), pipe spacing (S), pile conductivity (K_p), pipe conductivity (K_t), soil conductivity (K_s), and heat transfer coefficient of the circulating water (H). The effects of these parameter can be observed in Fig. 7 (b).

From the comprehensive comparison of various parameters, it is evident that the number of pipes and pile length have the maximum impact on the thermal performance of energy piles. However, the

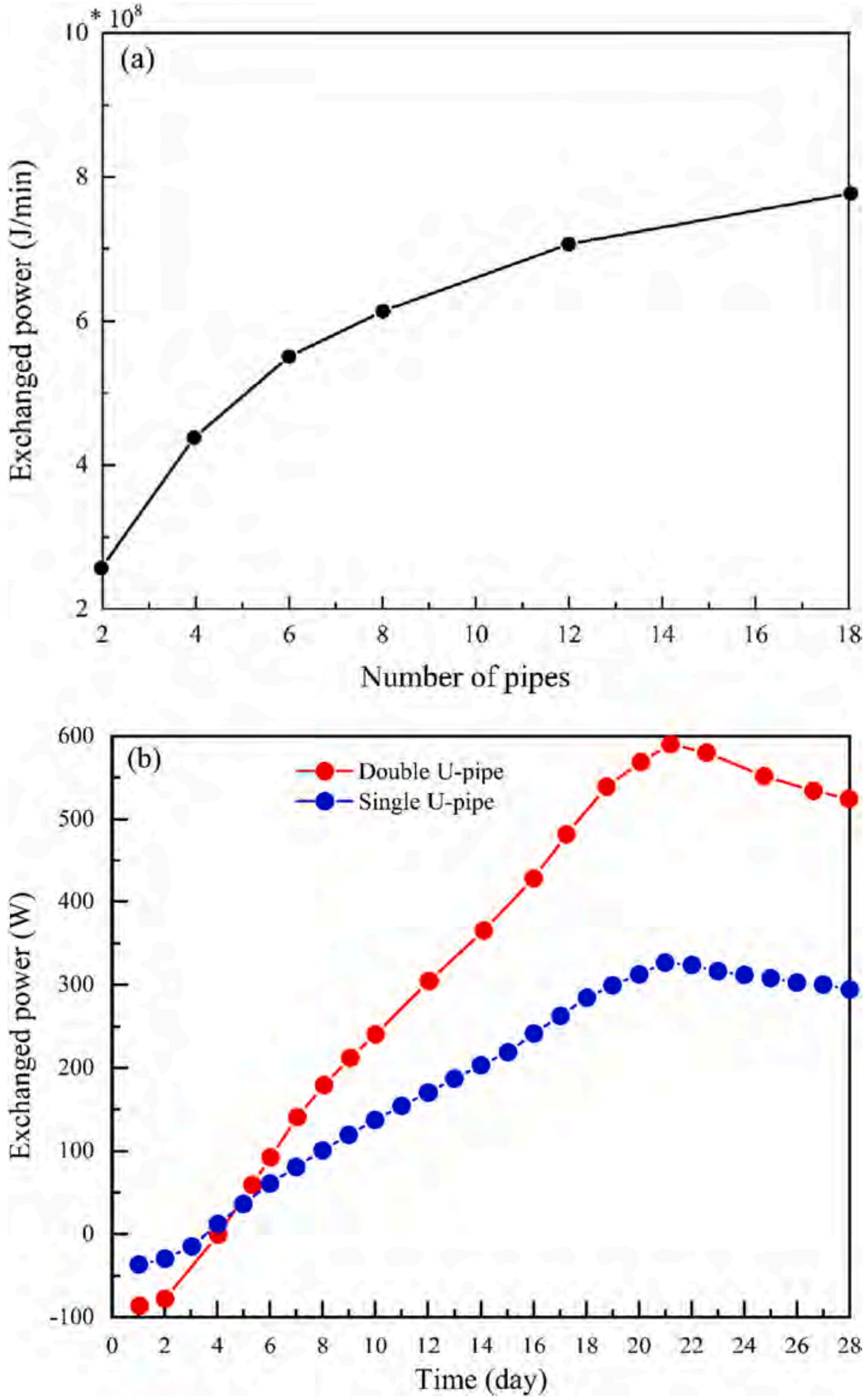

Fig. 3. The effect of number of pipes on the thermal performance of energy pile: (a) The exchanged power for different number of pipes [61]; (b) Energy extracted by single u-pipe and double u-pipe within 28 days [111].

determination of pile length is contingent on geological conditions and bearing requirements in practical applications. Therefore, optimizing the number of pipes is crucial for improving the thermal performance of energy piles. It should be noted that although the number of pipes can be independently determined, blindly increasing the number of pipes is not feasible. The limitations of pile diameter and the thermal interference between pipes need to be considered in the design. In addition, from a cost-benefit perspective, the benefits of additional pipes decrease with the addition of more pipes. The effect of the thermal resistance of the concrete cannot be ignored either. However, optimizing this parameter is challenging as the thermal resistance of concrete depends on its aggregate characteristics and mix ratio, and the primary function of the pile body is for bearing services. Based on the earlier analysis of the impact of pile diameter, although its effect on the thermal performance of energy piles is limited, prioritizing larger pile diameters in the design process is advisable. While reducing the thickness of the concrete

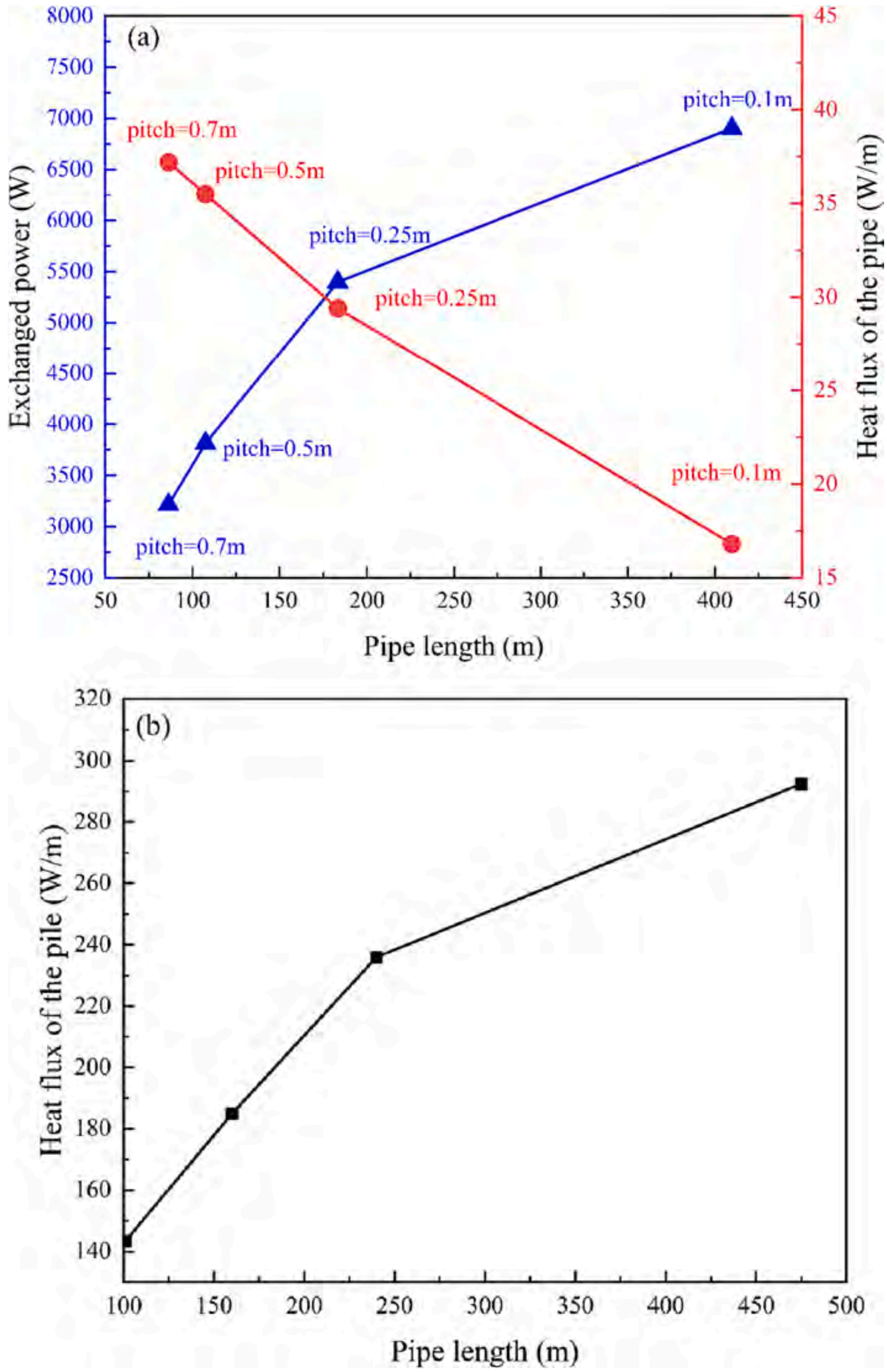

Fig. 4. The effect of pipe length on the thermal performance of energy pile: (a) Exchanged power (left axis) and heat transfer rate per unit of length of pipe (right axis) with different pipe length [62]; (b) Heat of flux of pile along with different heat exchange pipe length [66].

protective layer is advantageous for the heat exchange of pipes, the specific thickness setting should consider the thermal–mechanical effects of the pile body comprehensively.

Furthermore, when considering the influence of the key parameters mentioned above on the heat transfer performance of energy piles, it becomes evident that an augmentation in the contact area between the pipe and the concrete pile positively contributes to the improvement of heat transfer performance [42–45]. The increase in the number [40,61], diameter [67], and length of pipe [66] can all improve heat transfer performance by increasing the contact area.

3.2.8. Pile group arrangement

Additionally, beyond the design of individual piles, the rational design of pile groups is a crucial aspect of energy pile systems. According to You et al. [69], the efficiency of the energy pile group with a spacing of 7 m is higher than that with a spacing of 3 m. Regarding pile layout, a linear arrangement of energy piles proves more efficient than a stripe-shaped pile group or a rectangular pile array. Alberdi-Pagola et al. [70] redesigned an existing pile group by simultaneously considering the maximization of the distance between piles and the minimum number of energy piles required for the building’s thermal load, reducing the number of piles in the redesigned pile group by about 1/4,

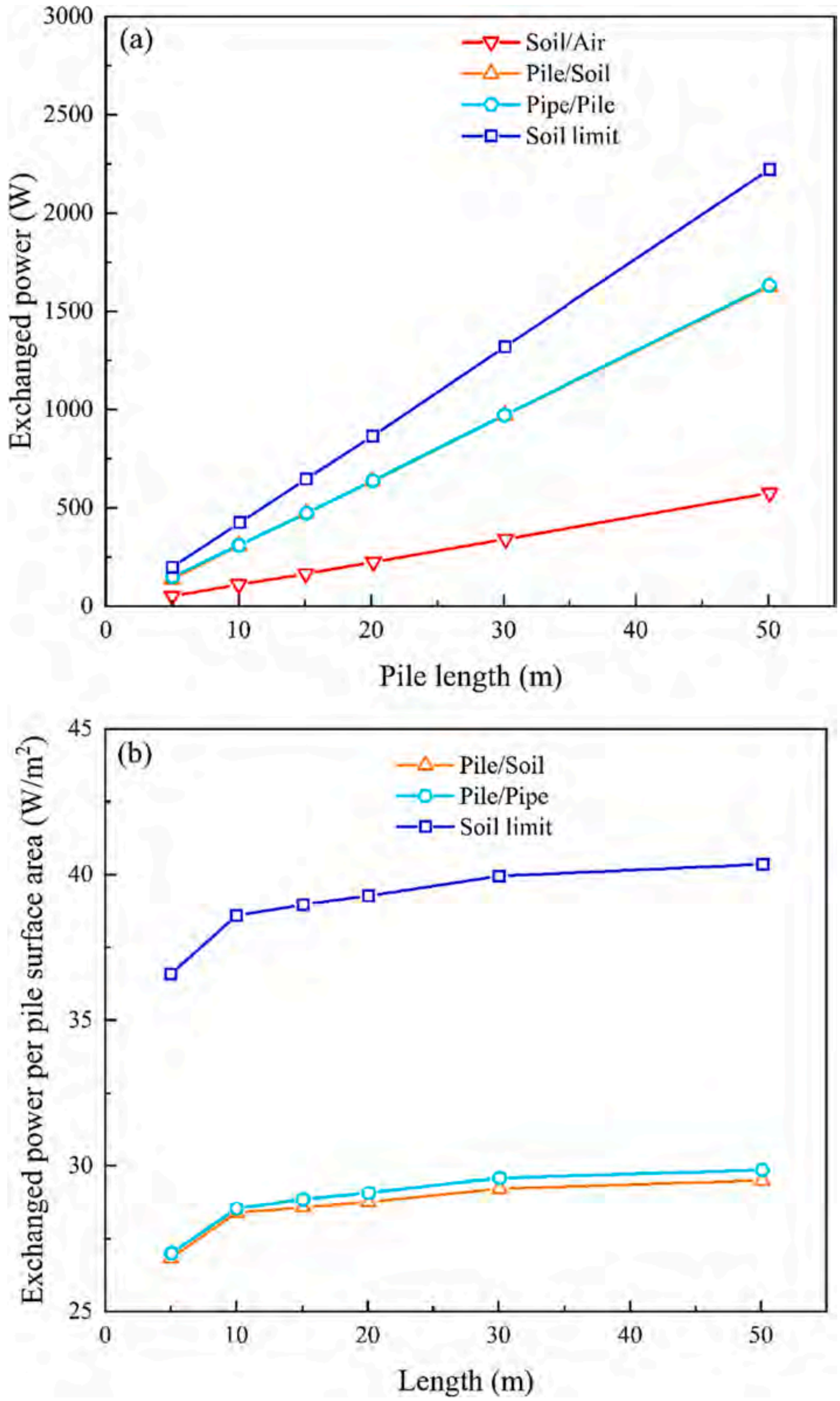

Fig. 5. The effect of length of pile on the thermal performance of energy pile: (a) Total exchanged power vs pile length at different interface [59]; (b) Exchanged power normalized by pile surface area vs pile length at different interface [59].

and significantly improving the efficiency of individual piles. Mehrizi et al. [37] proposed that different pipe-shaped energy piles have different influence radius, and during construction, the radius beyond the determined range should be exceeded to avoid mutual interference. In their study, the influence radius of a single-U shaped energy pile was 1.5 m, and that of a W-shaped energy pile was 2.5 m. Lyu et al. [68] found that the heat transfer rate of corner piles in clover and square pile group layouts was 6.8 % and 9.9 % higher than that of central piles. If only considering the thermal performance, they suggest that the pile spacing should be greater than 6.8 times the pile diameter. Tiwari et al. [112] proposed that when normalized spacing $s/d \leq 15$ (s is center-to-center spacing between two piles, d is the diameter of the pile), the power output from the pile group is less than the cumulative power output from the same number of isolated piles.

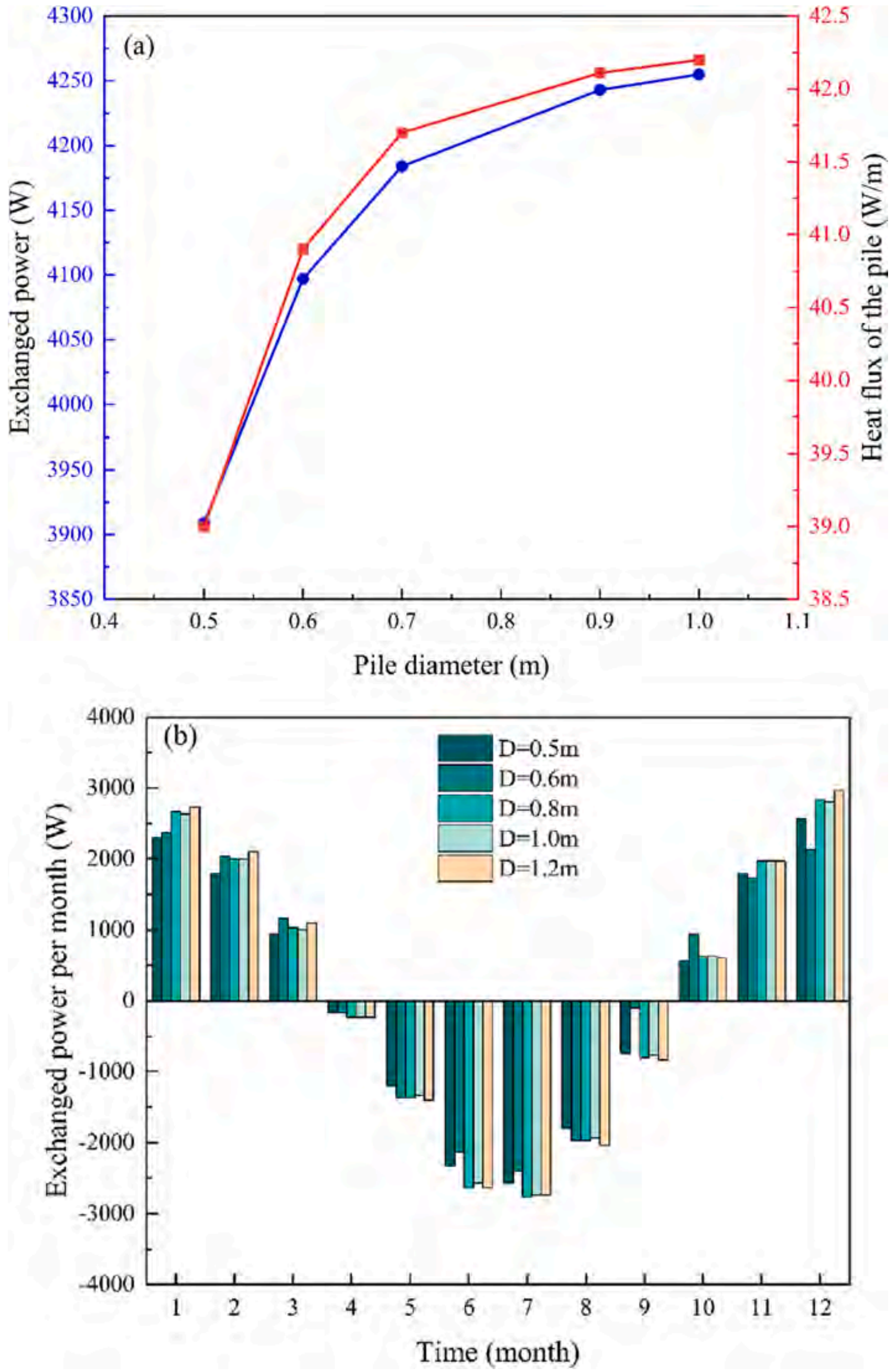

Fig. 6. The effect of length of pile on the thermal performance of energy pile: (a) Total exchanged power and heat transfer rate per unit length of pipe for different pile diameter [62]; (b) The monthly heat exchange for the different pile diameter [46].

Pile group layouts have a significant impact on the overall system and the efficiency of individual pile. Considering the mutual influence between energy piles, the pile spacing and pile layout should be given priority in the design. The spacing between thermal-active piles should exceed the influence radius wherever possible. On the other hand, the balance between the thermal efficiency of the single pile and the total amount of energy supplied also needs to be considered. To meet the total thermal demand of the building, the thermal efficiency of the single pile may be sacrificed for the placement of more thermal-active piles, increasing the total exchanged power.

4. Decarbonization considerations in construction and demolition stage

4.1. Construction method

Throughout the lifecycle of energy piles, the construction phase significantly impacts overall efficiency and economic costs. A reduction in efficiency necessitates more conventional energy during operation, diminishing the carbon reduction potential of energy piles.

Currently, scholars have summarized the installation methods of geothermal loops for various pile foundation technologies. For rotary

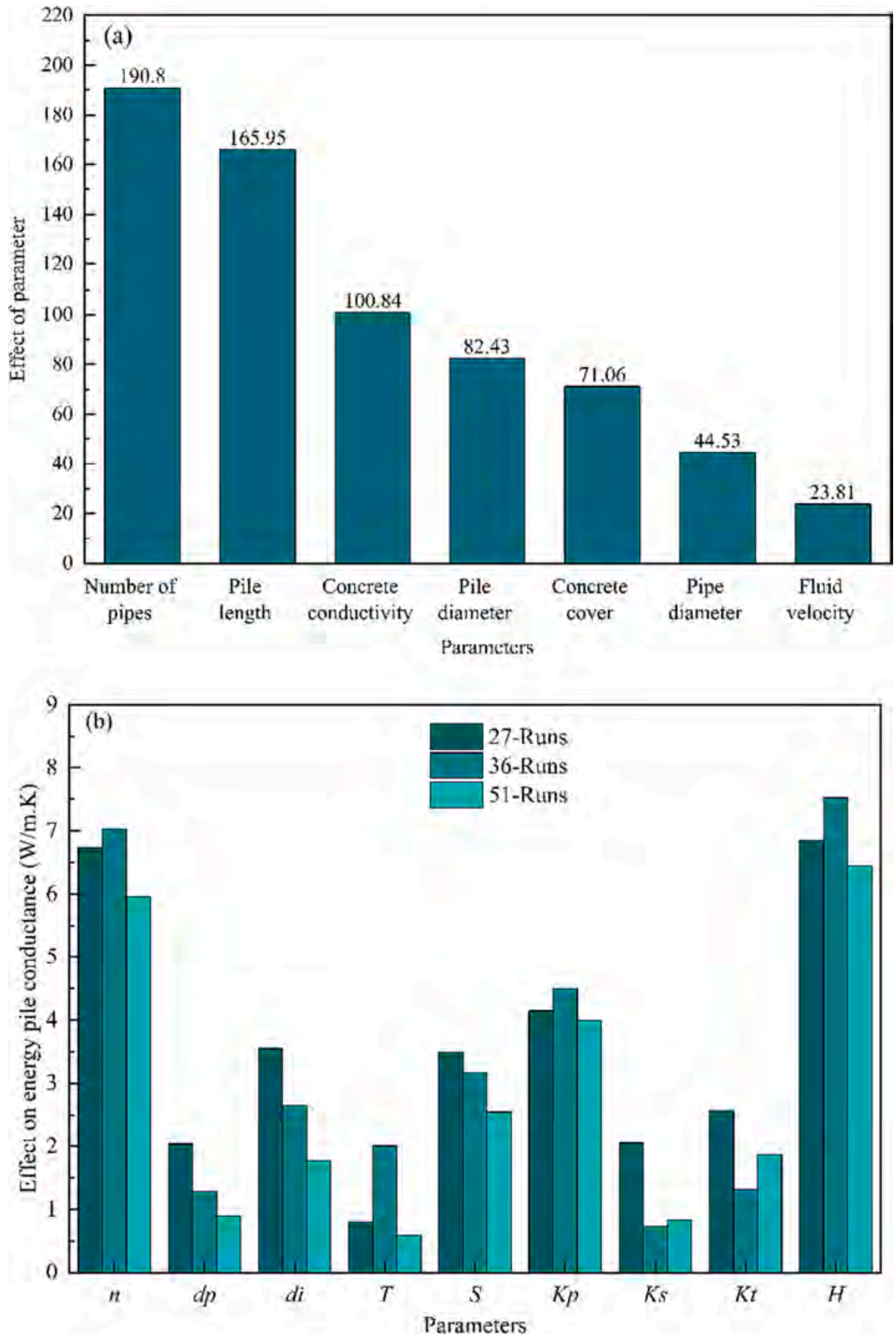

Fig. 7. The importance of different parameters on the thermal performance of energy pile: (a) The ranking of importance of parameter [61]; (b) The effect of the investigated parameters on energy pile conductance [79].

drilling piles, Amis et al. [71] indicated that the heat exchanger pipes can be installed inside the reinforcing steel cage, and the pipes can be allowed to hang below the cage to fully utilize the depth of the pile. During construction, a small amount of additional steel reinforcement can prevent the problem of pipes floating and not being fully utilized due to their buoyancy. For driven cast in-situ piles, Amis et al. [71] proposed that it is necessary to add a steel reinforcement throughout the length of the pile to avoid the problem of concrete "necking down" during casing withdrawal. Loveridge and Cecinato [72] discussed the construction differences and measures for continuous flight auger (CFA) piles, where steel cages are placed after pumping the borehole with a helical auger. This limits pipe length to the steel cage's range, requiring separate installation for full-depth requirements. Park et al. [26] evaluated the feasibility of installing multiple pairs of pipelines in large-diameter cast-in-place concrete piles. Large-diameter piles provide more pipeline space, but due to the limited surface area of the reinforcing cage, they can be installed on the outer and inner circumferences of the reinforcing frame separately. When installing multiple pairs of pipes, the complicated pipe connection at the pile head needs to be considered. During construction, it is necessary to distinguish the inlet and outlet of each pair of U-shaped heat exchange pipe. Fig. 8 and Fig. 9 summarize the common construction processes for energy piles. Ensuring quality in each construction phase is crucial for efficient energy pile operation, subsequently reducing carbon emissions during operation.

The demolition stage of energy pile has not been extensively studied. However, recycling and reusing waste from energy pile demolition could

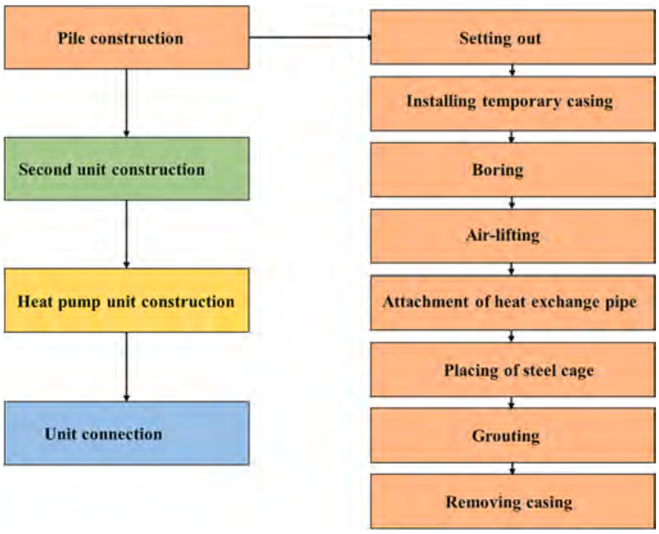

Fig. 8. Construction flow chart of energy pile system.

be a viable measure for further reducing carbon emissions in line with decarbonization goals.

4.2. Construction materials

During the construction phase, the selection of building materials for energy piles to reduce carbon emissions primarily involves enhancing the operational efficiency of energy piles and minimizing the embodied carbon of the materials.

Current research focuses on utilizing phase change materials (PCMs) to enhance the operational efficiency of energy piles. Bao et al. [80,113] encapsulated phase change paraffin in hollow steel balls within concrete, creating energy piles with PCM. Their findings indicate that PCM energy piles consistently exchange more power than traditional concrete energy piles. Based on this, Cui et al. [114] explored further, noting that PCM could reduce the water absorption capacity of concrete. To address this, they added steel fibers to PCM concrete, limiting water absorption while improving thermal conductivity, resulting in a 71 % increase in thermal conductivity. Cao et al.[81,83] employed the Taguchi-Grey relational analysis method to investigate the impact of PCM in precast high-strength concrete energy piles. They concluded that the increased latent heat and thermal conductivity of PCM could enhance the thermal efficiency of PCM precast high-strength concrete energy piles. However, Mousa et al.[115] pointed out that when PCM reaches a complete state, it may have a negative impact on the thermal performance of energy piles. The location of PCM in optimizing energy piles is also a crucial consideration.

In addition to using PCM to improve the thermal efficiency of energy pile operation and reduce operational carbon emissions, scholars also aim to minimize the embodied carbon in concrete piles. Shen et al. [77] introduced alkali-activated concrete in energy piles, observing improvements in thermal properties and a 32 % reduction in CO_2 emissions compared to Portland cement concrete energy piles. Alkali-activated concrete energy piles also extracted 17 % more thermal energy. While extensive studies on low-carbon energy piles have been conducted,

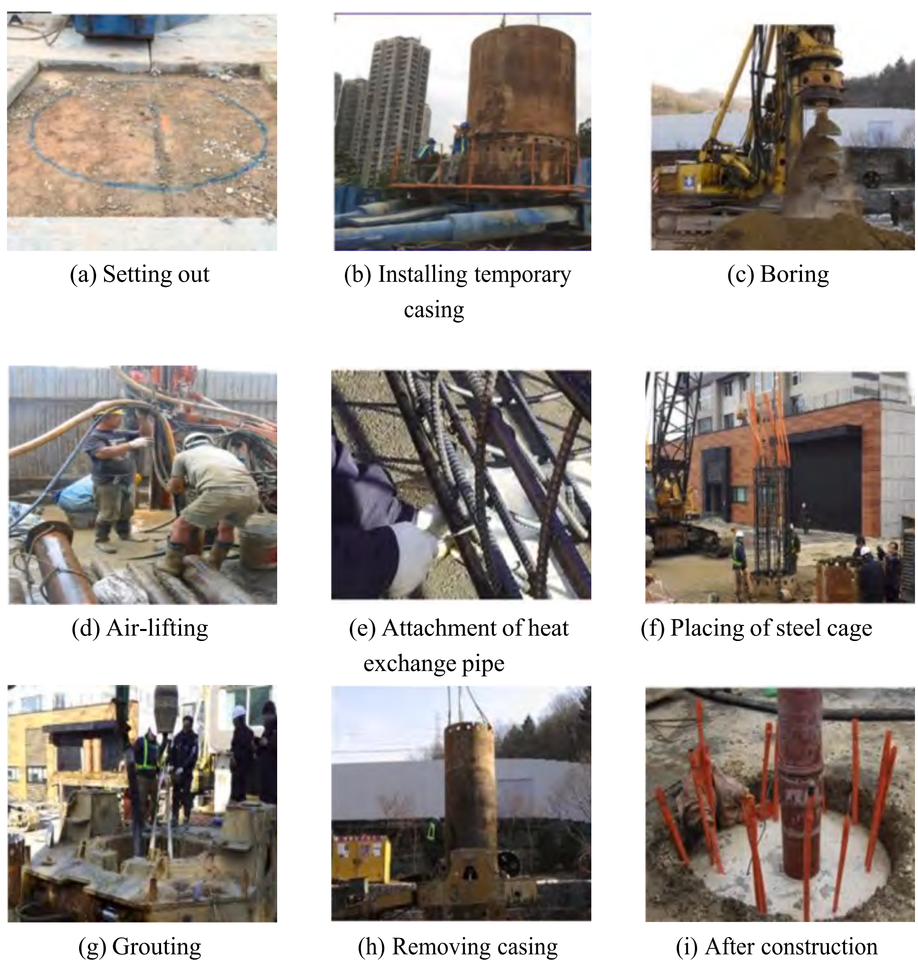

Fig. 9. Construction flow chart of energy pile system [25].

research on low-carbon concrete remains in its early stages. The thermomechanical properties of low-carbon concrete with different additives still require exploration [116–121] (see Table 3). Investigating the thermomechanical properties of low-carbon concrete and assessing the economic feasibility of using it in energy piles are crucial steps toward further reducing the embodied carbon of piles.

5. Decarbonization consideration in operation stage

5.1. Monitor method

To address the scarcity of quantitative analysis regarding the carbon reduction impact of energy piles, this section aims to consolidate methods for evaluating such reductions based on existing literature, and it will outline the essential monitoring data required for precise quantitative analysis.

The total CO_2 emissions caused by the operation of HVAC systems can be calculated based on the local energy structure. Some studies [15,24] consider CO_2 emissions related to electricity consumption and natural gas combustion, with a specific study [16] examining the reduction in CO2 emissions attributed to variations in electricity consumption. The CO_2 emissions of HVAC systems can be calculated by the Eq. (1) [24].

$$Total\ \ CO_2\ \ Emission = f_e \times E_{elec} + f_n \times E_{gas} \tag{1}$$

where f_e is the electricity-related CO_2 emission factor and E_{elec} is the electricity consumption, f_n is the natural gas-related CO_2 emission factor and E_{gas} is the natural gas consumption.

In an energy pile system, the energy flux received by the secondary circuit comprises a blend of energy extracted from the ground and the external power required to operate the heat pump (Fig. 10). This configuration enables the energy output after the heating pump to surpass the energy input for operation, implying that more energy can be supplied while consuming the same amount of electricity. Generally, the thermal performance of an energy pile system can be assessed using the coefficient of performance (COP).

Several studies on the COP of energy pile system have been collated, as depicted in Table 4. In Ref. [25,32,122–124], the COP of energy pile system typically ranges between 3.5 and 4.5, which means the secondary unit can obtain approximately four times more energy, with one portion of electrical input. The decrease in the reliance on fossil fuels for electricity generation underscores the carbon reduction benefits of energy piles.

In the process of calculating the emission reduction benefits of energy piles, the amount of energy heat exchange rate Q_{prim} provided by the primary circuit can be calculated by monitoring temperature sensors placed at the inlet and outlet, using Eq. (2)[113]. The power consumed by pile system P_{HP} can be measured by cumulative power meter. Then, the heat flux in secondary circuit can be calculated, using Eq. (3)[106]. The equivalent electricity demand of a traditional system can be evaluated based on Q_{sec}. After calculating the energy consumption of both the energy pile system and the traditional system, the CO_2 emission reduction can be calculated according to the above Eq. (1).

$$Q_{prim} = c_p \rho v \delta T = c_p \rho v (T_{out} - T_{in}) \tag{2}$$

$$Q_{sec} = Q_{prim} + P_{HP} \tag{3}$$

where Q_{prim} is the heat exchange rate (W),c_p is the specific heat capacity of the circulating water (J/(kg °C)), v is the velocity of the circulating water (m/s), ρ is the density of the circulating fluid (kg/m^3), δT is the difference between the outlet temperature (T_{out}) and inlet temperature (T_{in}) (°C), Q_{sec} is the heat flux in secondary circuit (W), P_{HP} power consumed by pile system (W).

Other data crucial for assessing thermal performance includes monitoring surrounding soil temperature and heat transfer fluid flow over time. During the long-term operation of the energy pile system for heat extraction/injection, the loss/accumulation of underground heat can influence the underground temperature. Significant alterations in the initially stable ground temperature may result in decreased efficiency after several years of operation [126]. Additionally, it is essential to monitor and control the flow rate within a reasonable range. Flow rates that are excessively fast or slow can lead to insufficient heat exchange or low heat transfer rates.

5.2. Optimization operation

Currently, there is less focus on the operational optimization of energy systems compared to design optimization. Allen Bowers et al. [129] grouped the piles based on their location. By operating different groups of piles at different extraction rates and by running piles in groups from the outside to the inside, the ground temperature variation is optimized, avoiding thermal efficiency loss. You et al. [86] conducted numerical simulations to compare the thermal performance of the energy pile system under four zoning operation strategies. The study found that zoning operation effectively alleviates soil thermal imbalance, improving the system's COP. In Ref. [82–85,130–132], the improvement of the thermal performance of energy piles by different operation modes is explored. Compared to the conventional continuous operation mode, the intermittent operation mode (e.g.,16 h operation with 8 h rest, and 8 h operation with 16 h rest) allows for a higher heat exchange rate. At the same time, the intermittent mode of operation allows for less variation in ground temperature. The major findings of these operation optimization studies reviewed are presented in Table 5.

6. Decarbonization assessment

6.1. Case studies

The application of energy piles has significant implications for reducing CO_2 emissions. In current cases, energy piles are mostly used in commercial or office buildings. Simulating the long-term operation of the energy piles allows the calculation of the energy supplied by the system, and when combined with the local energy structure, it provides

Table 3
Summary of the basic information in the studies about the low-carbon concrete.

Ref.	Basic information	Conclusions
[116]	Supplementary cementitious materials (Fly ash)	Replacing 20 % clinker with glass cullet can reduce energy consumption by about 16 % and greenhouse gas emissions by 17 %.
[117]	Supplementary cementitious materials (Fly ash)	Fly ash can reduce the carbon dioxide emissions of concrete by 13 % to 15 %.
[118]	Supplementary cementitious materials (Fly ash)	The CO_2 emission of concrete with 50 % ordinary Portland cement replaced by fly ash is 41.42 % lower than that of full cement concrete.
[119]	Low-carbon cementitious binders (Geopolymers)	Compared with ordinary Portland cement, geopolymer concrete has an estimated reduction of 44 % to 64 % in greenhouse gas emissions.
[120]	Low-carbon cementitious binders (Metakaolin geopolymer)	Compared to cement concrete, geopolymer concrete reduces global warming potential by 61 %.
[121]	Low-carbon cementitious binders (Calcium sulfoaluminate)	The direct CO_2 emissions of Calcium Sulfoaluminate clinker are 34 % lower than those of ordinary Portland cement clinker.

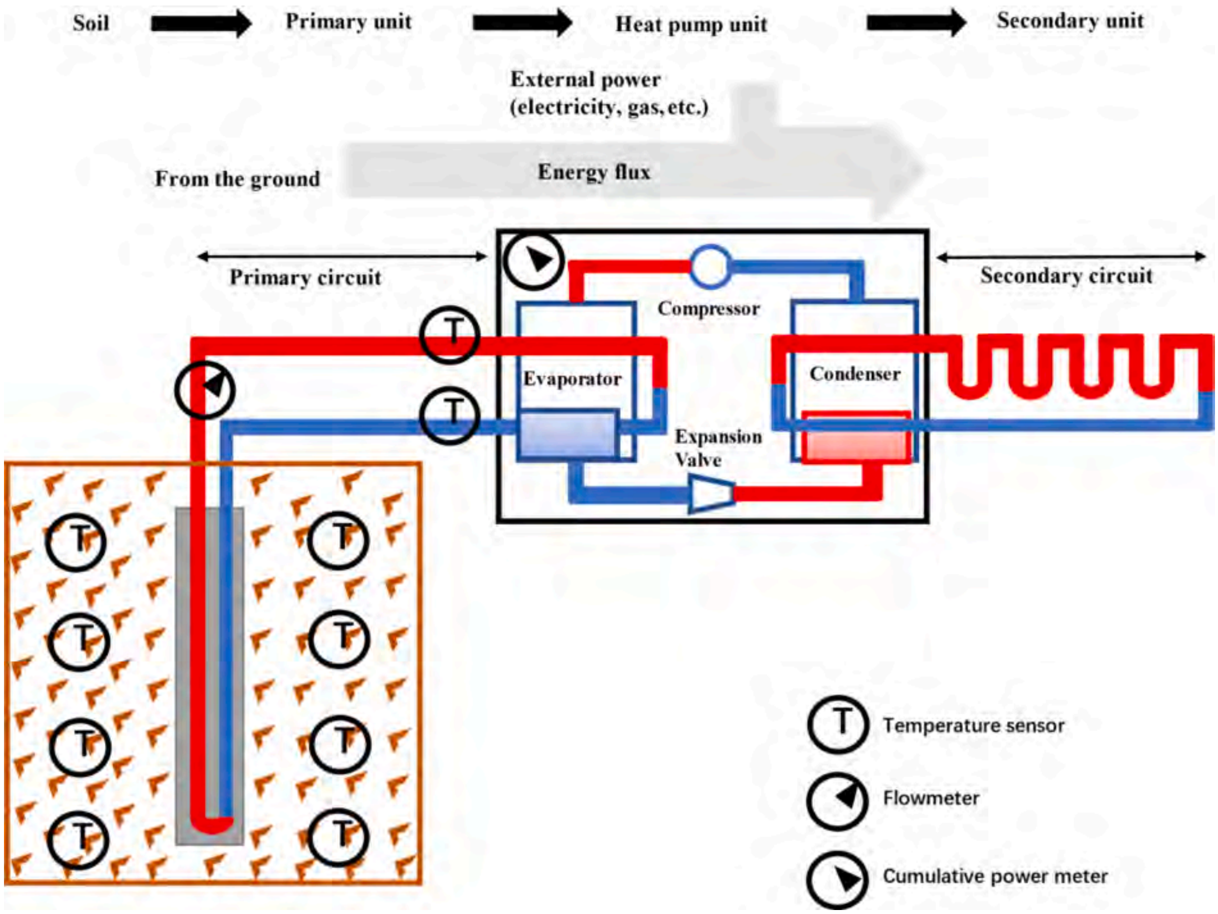

Fig. 10. Basic principle of Thermal performance monitoring [106,127,128].

an estimate of the long-term carbon reduction potential of energy piles. This section reviews the quantification studies of energy pile emissions reduction to demonstrate the low-carbon characteristics of energy piles more intuitively.

The multi-functional hall (Europe) [106,108]: The multi-functional hall was designed with a capacity of 8000 persons, using 320 energy piles (18 m) for space heating and cooling. The total length of the heat exchange pipes is approximately 65 km. The system can save 85,000 m^3 of natural gas per year, equivalent to a reduction of 73 tons of CO_2 emissions.

The low-energy shopping center (Austria) [106]: The shopping center used 650 thermal-activated piles (diameter D = 0.9 m, some piles have a diameter of D = 1.2 m, depth = 50 m). By using energy piles instead of traditional heating/cooling systems, the center saved nearly 550 tons of CO_2 emissions. Excess geothermal energy is transported to the public district energy supply line.

The Liberal Arts Building on the Texas A&M University Campus (Texas, USA) [16]: The five-story building covers a total area of 11,575 m^2 on a 2,885 m^2 land area, based on 263 foundation piles. The climatic condition is warm humid temperate climate. The temperature range is usually between 4.4 °C and 35 °C throughout the year. The warm season have a daily average high temperature of 31.4 °C or above, lasting from the end of May to the end of September. By monitoring the operation of the conventional HVAC system for one year, the total electricity consumption was determined to be 817,951 kWh. Simulations were performed for the operation of 263 energy piles (single-u pipe, pile spacing = 1.46 m, pile diameter = 0.45 m, pipe spacing = 0.2 m, pile length = 17.4 m, total pipe length = 4,734 m,$\lambda_{concrete}$ = 2.30 W/m.Kλ_{soil} = 1.87 W/m.K) in the building for 30 years. The use of this system will reduce total electricity consumption by 5,573 MWh over 30 years. This reduction in electricity consumption will lead to a total reduction of 3,932 tons of CO_2 emissions over 30 years.

A seven-story building (Naples, Milan, Italy) [15]: The building has a total heat transfer area of 1609 m^2 and a gross heated volume of 5991 m^3. Operation in two different climate zones is considered for the same building: Naples in southern Italy with an external design temperature of 2.0 °C in winter, and Milan in northern Italy with an external design temperature of 5.0 °C. The temperature inside the building is assumed to be uniform, with a temperature of 20 °C during the heating season and 26 °C during the cooling season. The building has 24 energy piles, each 25 m long and consisting of four u-shaped pipes per pile, with a total pipe length of approximately 4800 m. A horizontal connection of about 500 m was also considered. The net energy required for heating and cooling are provided. In Naples, the cooling energy demand is about 39,500 kWh/year, while the heating energy demand is about 15,500 kWh/year. In Milan, the cooling energy demand is about 25,100 kWh/year, while the heating energy demand is about 52,700 kWh/year. Based on a 20-year simulation, it was concluded that the use of energy pile systems can reduce greenhouse gas emissions by approximately 20 % for the building in Naples, and by no more than 10 % for the building in Milan.

In addition to the above cases, Han et al. [24] conducted a comparative study of energy pile system against a water source heat pump (WSHP) system + an evaporative fluid cooler + a natural gas boiler and an HVAC system that directly utilized regional heating and cooling as energy sources. Regardless of location and climatic zone, the energy pile system was found to emit the least amount of CO_2, as illustrated in Fig. 11. This research highlights the versatility and superiority of energy pile systems across different environments, resulting in a significant reduction in CO_2 emissions. Across the eight cities studied,

Table 4
Summary of the basic information in the studies about the COP of energy pile system.

Ref.	Basic information	COP
[25]	Pipe: Diameter: inner diameter = 21 mm outer diameter = 27 mm 5-pair-parallel U-type, Length = 130 m:8-pair-parallel U-type Length = 208 *m* 10-pair-parallel U-type Length = 260 m; S-type Length = 160 *m* Coil-type 500 mm coil pitch Length = 101 *m* Coil-type 200 mm coil pitch Length = 240 *m*	COP = 2.91; The system performance factor (SPF) = 2.78 (heating mode) COP = 3.40; SPF = 3.14 (cooling mode)
[32]	Pile: Length = 9 m; Diameter: inner diameter = 232 mm; outer diameter = 302 mm Pipe: Shape: U-shaped; Diameter inner diameter = 28.8 mm; outer diameter = 34 mm	COP = 3.9 SPF = 3.2
[122]	Pile: Length = 15 m; Diameter: inner diameter = 0.34 m; outer diameter = 0.5 *m* Pipe: Shape: Coil-shaped; Daimeter:25 mm Length = 196 *m*	COP = 3.9–4.3
[123]	Pile: Length = 10 m; Diameter = 0.3 *m* Pipe: Shape: U-shaped; Diameter: inner diameter = 0.032 m; outer diameter = 0.013 *m*	first year operation: the average COP = 3.40 (heating mode) the average COP = 4.63 (cooling mode) the tenth-year operation: the average COP = 3.82 (heating mode) the average COP = 4.31 (cooling mode)
[124]	150* reinforced concrete piles, 13 m long 10 * 180 m long pipes buried in the base slab	The COP of the heat pump units of the energy pile varies in the range of 4.2–4.7 and the average daily COP of the system varies in the range of 3.5—3.9.
[125]	Pile: Length = 10 m; Diameter = 0.8 *m* Pipe: Shape: spiral-shaped; Diameter inner diameter = 26 mm; outer diameter = 32 mm; Pitch = 0.2 m; Length = 85.3 *m*	COP = 4.7–4.8 (heating mode) COP = 4.4–4.7 (cooling mode)

energy piles achieved an average reduction in CO_2 emissions ranging from 25 % to 36 %.

The existing literature underscores the noteworthy advantage of the energy pile system in reducing greenhouse gas emissions, a critical aspect in its feasibility assessment. However, there is currently a scarcity of long-term monitoring data on the application of energy pile systems in buildings, necessitating further research on the emission reduction effects of energy pile systems in buildings situated in diverse climatic regions. Moreover, the present research on the emission reduction effects of energy piles predominantly centers on lowering operating carbon, with insufficient attention to embodied carbon. A comprehensive examination of both operating and embodied carbon can provide insights into the low-carbon performance of energy piles and guide further research directions for more effectively reducing carbon emissions. Energy piles, given their advantage of not requiring additional drilling compared to traditional ground source heat pumps, merit prioritized consideration in engineering projects. Governments should augment investments in energy piles, considering environmental factors such as greenhouse gas emissions, through policy and funding support.

6.2. Life cycle assessment

In the application of energy pile technology, it is crucial to not only assess energy efficiency during the operational stage but also consider its environmental impact throughout its entire lifecycle for a comprehensive evaluation of its engineering applicability.

Table 5
Summary of the basic information reported in the main optimization operation studies reviewed.

Ref.	Optimization objective	Optimization variables	Main findings
[129]	Minimize the amount of energy lost in the ground	Combinations of heat injection and extraction	Operating the single pile in the pile group from outside to inside depending on their location and operating the single pile in the pile group at different heat extraction rates (high extraction rate for the outer piles and low extraction rate for the inner piles) can result in less variation in ground temperature.
[86]	Alleviate the soil thermal imbalance, improve thermal performance of the system	Operational pile group	Continuous heat extraction will lead to the cold accumulation, which can be relieved by injecting dense heat into center of pile group or extracting heat from outer layer of the pile group. The heating COP can be improved from 3.297 to 3.432 by using zoning operation strategy.
[82]	The thermal and mechanical responses of energy pile	Operation mode: 16 h-on, 8 h-off	The heat exchange rate under intermittent operation is 53.5 % higher than under continuous operation.In the intermittent operation, the accumulated temperature decrease is smaller. Intermittent operation induced lower thermal loads on the foundation and the mechanical response of the pile is reversible.
[83]	The heat exchange rate of energy pile backfilled with PCMs	Operation mode: 6 h-on, 18 h-off 8 h-on, 16 h-off 16 h-on, 8 h-off 18 h-on, 6 h-off	The heat exchange rate of energy pile tends to decrease as the operating time increases. The enhancement effect of intermittent operation on the heat transfer performance of the energy pile backfilled with PCMs is more obvious because PCMs can recover to their initial state under the intermittent pattern.
[84]	The system performance for the long-term operation	Operation mode: 10 h-on,14 h-off	The system maximum and minimum thermal energy output is smaller under the intermittent operating condition. Intermittent mode operation saves approximately 50 % of power per month compared to continuous mode operation. (From November to April, 43.4 %, 55.9 %, 55.6 %, 55.3 %, 46.9 % and 44.4 % respectively)

(*continued on next page*)

Table 5 (*continued*)

Ref.	Optimization objective	Optimization variables	Main findings
			From November to April, The mean monthly COPs of the intermittent operation mode are 3.63, 3.58, 3.45, 3.21, 3.25 and 3.34. The mean monthly COPs of the continuous operation mode are 3.32,3.27, 3.22, 3.03, 3.10 and 3.24.
[85]	The thermal performance of the energy pile subjected to cooling	Operation mode: 8 h-on, 16 h-off 16 h-on, 8 h-off	The intermittent mode of operation provides a significant improvement in average energy extraction. (8 h-on, 16 h-off: 40.9 % higher than continuous mode, 16 h-on, 8 h-off: 14.8 % higher than continuous mode) The shorter the running time, the lower the thermal impact on the ground, but the higher the average pile temperature during operation.

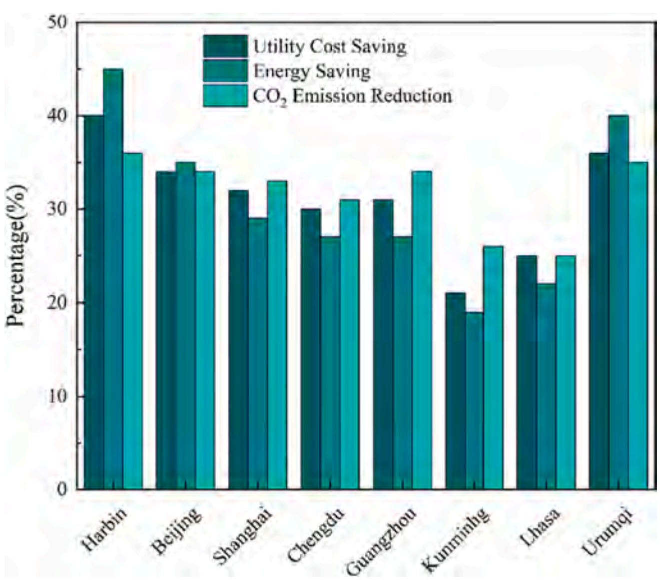

Fig. 11. Cost-saving, energy-saving, and CO_2 emission reduction of energy pile system [24].

For energy pile systems, the economic costs occur throughout their lifecycle, with energy savings realized during the operational stage. Environmental impacts can occur during production, installation, operation and demolition stage, as shown in Fig. 12 [133]. Sutman et al. [134] employed the life cycle assessment (LCA) methodology to evaluate the environmental performance of energy piles and compared it with that of conventional heating and cooling systems. The results demonstrated significant advantages of energy piles over conventional systems in four dimensions: equivalent CO_2 emissions, human health, resource consumption, and ecosystem quality. Furthermore, other LCA studies [133,135,136] focusing on geothermal energy for building heating and cooling have consistently shown that the application of geothermal energy is notably superior to conventional systems in terms of energy savings and environmental impact. It's important to note that the primary energy structure for power generation in different regions can influence the results of environmental assessments.

7. Challenges and future research directions

7.1. Potential challenges to wider adoption of energy piles for carbon reduction

7.1.1. Design perspective

In the design process of energy piles, the temperature change of the pile is an important parameter. Due to the transfer of heat through the pile body of energy piles, there is spatial difference and non-uniformity in the temperature distribution of the pile cross-section [137]. However, current design methods often rely on the maximum temperature change to calculate the thermo-mechanical response of the pile. This approach not only overlooks the nuanced influence of temperature changes on the pile, providing an unrealistic description of energy piles [138], but may also cause design redundancy and increased design costs. In addition, many commercial design programs use simplistic methods to consider temperature responses [18]. Common analysis methods, such as the line source model and cylindrical source model, neglect factors like axial heat flow along depth, soil surface heat flow, and bottom heat flow [139]. The application of simplified analysis methods can constrain the long-term analysis of the system's operation.

In the process of load calculation, there is a difference between the assessment of heating and cooling demand for buildings and the actual requirements. Current methods mostly lead to underestimation of demand [140]. On the other hand, since the number and size of energy piles depend on the mechanical requirements of buildings, the supply of heat load may not fully meet the demand, necessitating consideration of hybrid systems. Existing research primarily focuses on the analysis of single piles or pile groups, lacking studies on the design of energy pile hybrid systems. In hybrid systems, challenges such as accurately determining the heat load that each system can provide and determining the appropriate control mode need to be addressed.

An integrated platform for energy pile design remains a critical need, requiring ongoing development and enhancement. Existing design methods for traditional energy pile systems are often guided by singular objectives, lacking the capability to holistically consider relevant factors across different domains. This limitation is tied to the simplification methods employed during design and certain specific numerical calculation software [102]. Energy pile design necessitates the simultaneous consideration of load-bearing requirements and heating/cooling demands. The heat transfer occurring during energy pile operation may induce changes in local mechanical properties. During long-term operation, both the mechanical and thermodynamic properties of energy piles will inevitably undergo certain changes [141,142]. In addition, research on optimization design of energy piles is currently insufficient. Integrating various algorithms for optimizing energy piles has the potential to enhance overall system performance.

7.1.2. Construction perspective

The construction of energy piles mainly involves pipeline placement and fixing operations. Compared with traditional borehole GHE systems, energy piles have larger diameters, providing geometric flexibility for the internal heat exchange tubes. However, the increased geometric complexity also increases the uncertainty of construction quality [143]. Improper operations may cause pipe rupture and leakage of heat exchange fluid. In addition, non-standard construction may lead to the bending or blockage of the geothermal loop, causing deviations from the intended design during operation [71]. Furthermore, once the pile is completed and the upper structure starts construction, it will not be possible to repair or replace the pipeline of the energy pile. Any operational discrepancies arising from improper construction can only be addressed by integrating other systems.

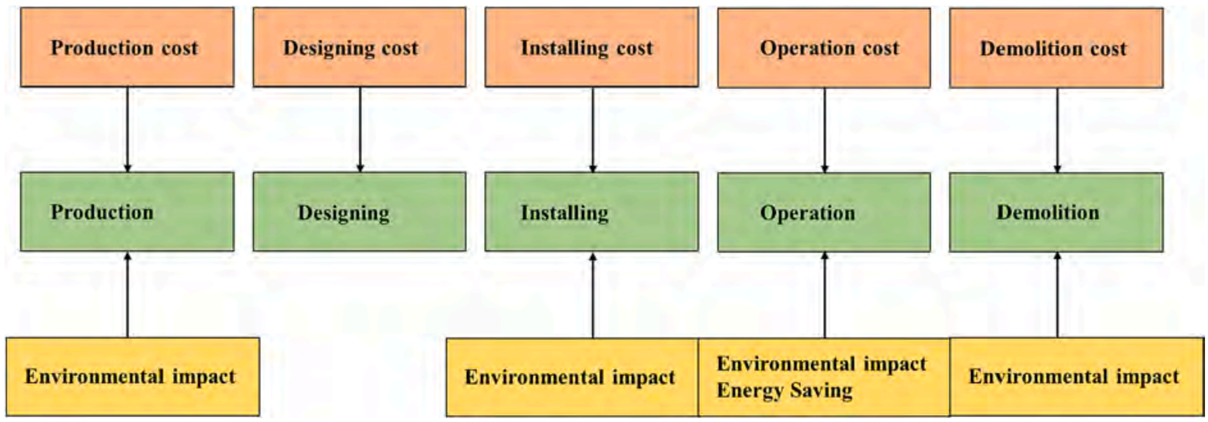

Fig. 12. Time period of sustainability aspects of energy saving measures [133].

7.1.3. Operation perspective

Current research lacks a comprehensive sensitivity analysis of energy piles and the application of rational optimization technique for their operation. The coupling of thermal and mechanical effects, as well as the interaction between piles and soil, presents a complex scenario. Studies indicate that the sensitivity of numerical prediction of energy piles is much more complex than previously thought by Caulk et al. [144]. With changes in external forcing such as mechanical loads or temperature variations, the impact of input factors (such as model parameters) on the prediction of different spatial aggregated model outputs will change [145]. However, there is currently little research on global sensitivity analysis of energy piles.

Operational optimization has demonstrated the potential to further improve the thermal performance of energy piles. Strategies such as zoning operation [86] or intermittent operation [85] can both improve system efficiency by mitigating soil thermal imbalance. However, current optimization studies often lack the use of specific optimization methods. Instead, they compare performance by setting different fixed values (e.g., comparing system efficiency under 8 h, 16 h, 24 h operation times). Such an optimization does not consider all solutions and the result may not be optimal.

7.1.4. Assessment perspective

There is a lack of comprehensive evaluation for the long-term operation of energy pile systems. Existing literature mostly focuses on the short-term thermal effects of energy piles, but the long-term operation of the system will inevitably lead to changes in its thermal efficiency [24]. Therefore, monitoring and evaluating the long-term operation of energy pile systems are crucial. Furthermore, a significant limitation to the widespread adoption of energy pile technology is the high initial investment cost. Conversely, its environmentally friendly characteristics offer substantial benefits [24]. Therefore, a comprehensive evaluation considering economic output and environmental benefits is essential.

Current literature on environmental analysis of energy piles predominantly focuses on the greenhouse gas emission reduction effect during the operation of energy piles but lacks a comprehensive evaluation of the environmental impact throughout their entire lifecycle. Energy piles have an impact on the environment during their manufacturing, installation, and operation stages. A comprehensive assessment is needed from the perspective of the entire lifecycle.

7.2. Future research and development of energy piles for carbon reduction

7.2.1. Design perspective

To advance the design of energy piles, it is essential to employ more design optimization techniques for exploring optimal design variables. In particular, Pareto-based methods and decomposition-based methods [146] can be used for solving MOO problems in order to fill the research gap in this direction.

There is a need for the development of specific guidelines and a compilation of typical case references for energy pile design applicable to different regions. In Ref. [24,134], it is evident that the energy, environmental, and economic benefits of energy pile systems are significantly influenced by the climate zone. For instance, applying energy piles in Harbin, located in severe cold zone, will contribute to 45 % energy saving, 40 % utility cost-saving, and 36 % CO_2 emission reduction. However, in Kunming, which is located in mild zone, the energy saving, utility cost-saving and CO_2 emission reduction will be 19 %, 21 %, 26 % respectively when the energy piles are used [24].

The construction and continuous improvement of an integrated design platform are essential. This platform should facilitate the incorporation of optimization algorithms, allowing for real-time adjustment of parameters and simulation of energy pile performance under various operating conditions.

7.2.2. Construction perspective

Lean construction principles have shown promise in maximizing value and minimizing waste, as seen in Ref. [147,148], where lean construction was implemented in the construction process of a steel structure building, resulting in a significant reduction of 43 tons of carbon lean construction [148]. It would be beneficial to explore the application of “lean principles” specifically in the construction of energy piles to assess the potential carbon reduction effects.

Encouraging research on prefabricated energy piles is essential. In the materialization stage, the production of building materials typically generates significant carbon emissions [149]. The implementation of prefabrication has the potential to reduce construction waste, increase material recycling rates, and consequently lower carbon emissions [150–152].

Further studies are necessary to investigate construction methods for different types of energy piles to prevent a loss of system efficiency due to improper construction. The development of a standardized construction manual based on successful existing experiences would contribute to the effective construction of energy piles.

7.2.3. Operation perspective

In terms of single pile operation, it is crucial to focus on key scientific issues such as “heat transfer mechanism of energy piles under air–soil coupling boundary” and “heat transfer basic theory of energy piles-building coupling”. A deeper understanding of these theories can provide valuable directions for optimization, and serve as a theoretical foundation for the development of software related to energy pile design.

From the perspective of pile group system operation, existing research on the operational optimization of energy pile groups has been limited to a simple approach based on a set of comparative values. To achieve an optimal solution, more sophisticated optimization techniques need to be applied, addressing the complexities inherent in the operation of pile groups.

From the perspective of overall system operation, considering that the heat load provided by energy piles is constrained by the size of the pile group, further investigation into hybrid systems combining energy piles with other HVAC technologies is essential to meet the energy demand of buildings. Additionally, research on control optimization and the application effects (e.g., energy efficiency, economic impact, and environmental impact) of hybrid systems is required.

7.2.4. Assessment perspective

The establishment of a standardized evaluation system that incorporates considerations for energy savings, environmental impact, and economic benefits is crucial for a comprehensive assessment of the advantages associated with energy piles. This standardized approach would serve to garner increased attention in this field. Moreover, there is a pronounced need for the routine collection and analysis of data pertaining to energy pile applications and case studies. The scarcity of literature detailing long-term operational monitoring results for energy piles and corresponding analyses of the economic and environmental benefits underscores the necessity for more research in this area. The integration of such data is paramount to comprehending the trends and limitations of energy pile technology applications.

8. Conclusions

This paper provides a comprehensive critical review on energy pile design, construction, operation, and assessment, particularly focusing on carbon reduction from a life-cycle perspective. The integration of life cycle assessment and existing case studies has demonstrated the advantages of optimizing energy piles for carbon reduction at different stages of their life cycle. Several key conclusions and suggestions of this study include:

- The energy efficiency of energy piles presents a substantial advantage in carbon reduction, achieving a noteworthy 75 % reduction in electricity consumption for the same energy output. This efficiency holds significant potential for making a substantial impact on carbon reduction efforts. However, it is crucial to calculate the actual carbon reduction considering the intricacies of the local energy structure.
- To maximize the carbon reduction potential of energy piles, it is recommended to employ advanced optimization techniques during both the design and operation processes. This involves moving beyond simplistic comparisons based on predetermined values for design and operational factors, enabling a more tailored and effective approach to achieve optimal efficiency.
- The construction stage and the selection of building materials for energy piles are frequently disregarded in terms of carbon emissions. To enhance their carbon reduction potential, integrating "lean principles" into the construction phase can optimize processes and minimize embodied carbon emissions. Additionally, exploring the use of low-carbon concrete for energy pile foundations holds promise for achieving a significant reduction in embodied carbon emissions.
- Despite a scarcity of comprehensive evaluations of energy piles, existing studies consistently confirm their substantial environmental advantages over conventional HVAC systems. To encourage wider application and awareness of energy piles, it is crucial to conduct more thorough evaluations that consider various factors influencing their environmental impacts.
- Considering the current global emphasis on carbon reduction and the broad applicability and advantages of energy piles compared to other energy technologies, their implementation for reducing the carbon emissions of HVAC systems holds tremendous promise. Energy piles present significant advantages in terms of carbon reduction benefits, and by addressing the recommendations outlined above and capitalizing on the global momentum for carbon reduction, the prospects for their widespread adoption in HVAC systems are exceptionally promising.

CRediT authorship contribution statement

Linfeng Zhang: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft. **Haozhe Han:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Wenxin Li:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing. **Kewei Guo:** Conceptualization, Formal analysis, Investigation. **Minglu Yuan:** Conceptualization, Formal analysis, Investigation. **Zhengxuan Liu:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing 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.

Data availability

No data was used for the research described in the article.

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