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Research Article

Cost Effectiveness of Energy Piles in Residential Dwellings in Australia

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Abstract

The cost effectiveness of energy piles used as part of Ground Source Heat Pump (GSHP) systems in residential buildings is presented. Structural piles can be used with a dual purpose of providing support to superstructures and of exchanging thermal energy with the ground, thus minimizing capital cost of GSHP systems associated with drilling. To exemplify the economic potential of energy piles, a case study of a representative residential building is undertaken. Results show that energy pile GSHP systems render annual gains of about $600 to $2900 (US dollars) in comparison with other conventional heating and cooling systems. This paper also briefly demonstrates the reduced available thermal capacity of energy piles, compared to traditional borehole ground heat exchangers, due to their inherent short depth and close spacing between piles. Despite this limitations, energy pile GSHP systems are able to satisfy the thermal energy needs for space conditioning of residential buildings.

Keywords: Ground source heat pumps; Energy pile; Geothermal; Economic feasibility; Temperate climate

Introduction

Ground Source Heat Pump (GSHP) systems are one of the most efficient and sustainable technologies to satisfy the space heating and cooling demands of buildings [1,2]. Given that the majority of the energy consumption within commercial and residential buildings is used for heating and cooling [3], utilizing such highly efficient systems is desirable. The GSHP system utilizes shallow geothermal energy by circulating a heat transfer fluid into the ground, commonly through closed loops. These loops are buried in the ground either horizontally in trenches or vertically in boreholes depending on the land availability, forming Ground Heat Exchangers (GHEs). In urban areas, due to the space limitations, vertical GSHP systems are most commonly used, but they are typically associated with high drilling costs. In fact, the cost of drilling and GHE installation accounts for about 50% of the total capital cost, with a mean value of USD 11,800 for a typical residential GSHP system in Australia [4,5]. Similar observations have been made around the world: a German study reported that drilling and GHE installation accounted for 51% of the capital cost [6]; another study found that particularly in the domestic market, the cost of ground loop installation is a significant barrier to the GSHP industry in the UK [7]. One way to mitigate the high drilling cost is to install the ground loops inside piles, converting them into GHEs knowns as 'energy piles' [8]. It is generally agreed that GHE-induced temperature variations have a negligible effect on bearing capacity of piles, and negligible thermo-induced settlement, expect in the case of normally consolidated clays [8-12]. Whenever pile foundations are used, the inclusion of pipe circuits may represent a cost-effective solution to GSHP systems. There are a number of papers discussing the thermo-mechanical response of energy piles in either numerical or experimental studies [9,10,13-16], and efforts have been made to determine G-functions to simulate the interaction between adjacent energy piles [17] and to facilitate the design and installation of energy piles [8]. However, little research has been conducted to assess the economic feasibility of such designs in comparison with conventional heating, ventilation and air conditioning (HVAC) systems [9,13].

This paper presents an introductory economic analysis of the utilization of energy piles for space heating and cooling in residential buildings located in regions that are predominantly founded on soft or collapsible soils that may require piled foundations such as the vast loess regions around the world [18,19]. To explore the economic feasibility of energy piles in these area, three different thermal loading scenarios are used in the analysis of a typical Australian dwelling. This article also considers the possible reduced thermal energy exchange capacity of energy piles when compared to borehole GSHP systems. Unless otherwise specified, costs are shown in US dollars throughout the article.

Description of GSHP Systems with Energy Piles

A schematic diagram of a common GSHP system with vertical boreholes is shown in in Figure 1A, while a GSHP system with energy piles is shown in Figure 1B. A generic GSHP system consists of three main components: a) a heat pump, b) ground heat exchangers, and c) a building distribution system. The most commonly used method of placing the GHEs is via vertical boreholes, as shown in Figure 1A. While vertical boreholes would normally have a depth beyond 50 m and a borehole diameter between 0.2 and 0.3 m, energy piles typically only range between 10 and 25 m depending on the depth to the bedrock but have a larger diameter of 0.6 to 1.2 m. The difference in geometry is better captured by the aspect ratio (AR), which is the length-to-diameter ratio of the GHE. Energy piles typically have ARs between 10 and 50, while boreholes have ARs beyond 200 [20]. Another difference is the spacing between two adjacent boreholes or piles. Piles are typically aligned with much shorter spacing (3–5 m) than boreholes (5–7 m). Despite the difference in geometry, both have embedded HDPE (high density polyethylene) pipes, enabling the flow of the circulating fluid. The circulating fluid is the heat carrier fluid, which enables space heating and cooling. In winter, the thermal energy from the ground is first passed to the circulating fluid and then transferred to the heat pump, where the energy is extracted and raised to be delivered to the building via a distribution system, such as fan coil units. In summer, the system then operates in a reversed cycle, rejecting heat to the ground to provide cooling (Figure 1A, 1B).

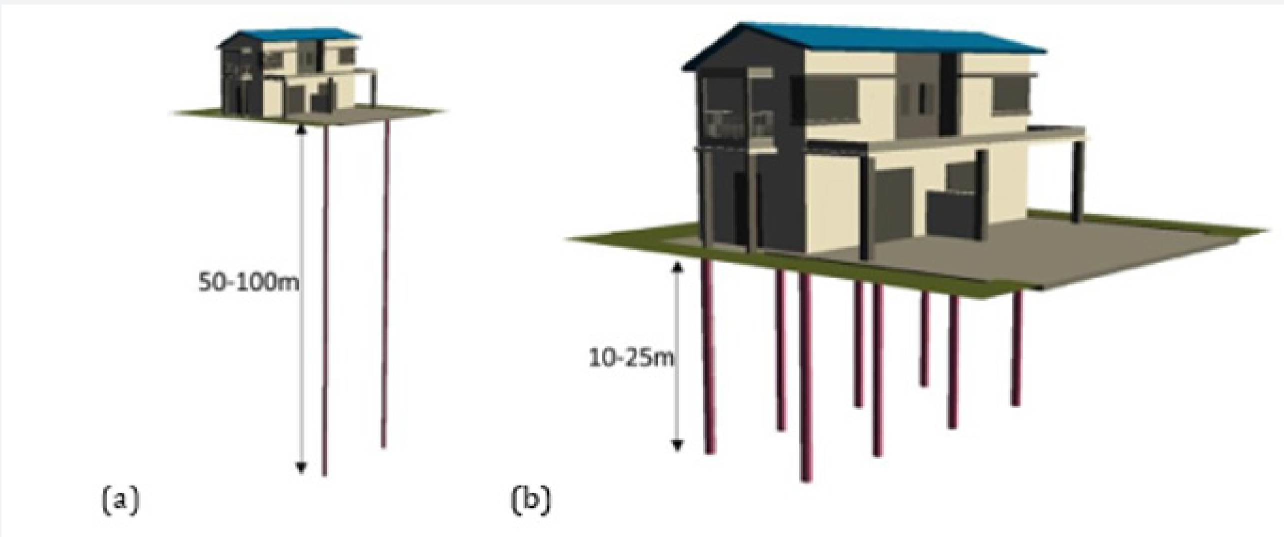

Figure 1: Schematic diagram of a residential building with (a) traditional borehole ground heat exchangers and (b) with energy piles.

The performance of a heating/cooling system is typically evaluated in terms of the coefficient of performance (COP). This is the ratio of energy output to energy input (i.e. electricity). The COP of a GSHP system depends on a number of factors, including the loop flow rate, ground thermal properties, and local climate [9], but is typically in the range of 3 to 5 [21-23].

Methodology

Economic indicators

For the past decade, the utilization of shallow geothermal energy has seen rapid growth in northern Europe, the United States, and China [21,24]. However, in regions with moderate climates, such as Australia, local residents are still wary of installing GSHP systems [21,24,25]. For the Australian geothermal industry, public awareness of such technology is lacking, and a perceived lack of financial benefit are regarded as the major drawbacks to its growth [4]. The perceived lack of financial benefit is further emphasized by the relatively high capital cost of GSHP systems, mainly contributed by the high drilling cost of vertical boreholes [4-7]. However, in the case of energy piles, the GHE loops are installed within the structural piles, and these piles are already required for structural reasons. Therefore, the drilling cost for GSHP systems with energy piles would be dramatically reduced. The only additional cost would be the raw material cost of HDPE pipes, labour cost of workers installing GHEs into piles, and potential delays to the construction program. The aim of this section is to present some economic indicators to assess the benefits of installing an energy pile GSHP system and whether the incremental capital compared to other conventional HVAC options can be justified. Economic indicators, such as the simple payback period and present value, are used extensively to judge the financial feasibility of GSHP systems [26–30]. However, these indicators have some inherent disadvantages (shown in Table 1) that may affect the decision making. In this paper, these indicators, as well as other more comprehensive ones, are used to provide a better illustration of the financial feasibility of an energy pile GSHP system. Brief descriptions of all the methods used herein are summarized in Table 1.

Table 1: Economic methods used to evaluate engineering projects [31].

	Brief Description	Key Equation	Disadvantages
PW (Present Worth)	Calculates the equivalent worth of all cash flows relative to the starting point. When PW > 0, the project is feasible.	$PW(i\%) = F_0(1+i)^o + F_1(1+i)^{-1} + \ldots + F_N(1+i)^{-N} = \sum_{k=0}^{N} F_k(1+i)^{-k}$	Future cash flow is assumed to be reinvested at a rate of MARR*.
AW (Annual Worth)	Annual equivalent savings minus annual equivalent capital recovery amount. When AW > 0, the project is feasible.	$AW(i\%) = R - E - CR(i\%)$ $CR(i\%) = I(A/P, i\%, N) - S(A/F, i\%, N)$	Future cash flow is assumed to be reinvested at a rate of MARR*.
SPP (Simple Payback Period)	Calculates the number of years required for cash inflows to just equal cash outflows.	$\sum_{k=1}^{\theta}(R_k - E_k) - I \geq 0$ *Simple Payback Period* = θ, such that	Does not consider the time value of money; does not indicate project desirability; results may be misleading.

* MARR refers to the Minimum Attractive Rate of Return. For non-business purposes, MARR is typically treated as equal to the interest rate of a savings account. For business purposes, MARR is normally

set by the top management to reflect the minimum rate of return required for the company's operation.

Variables: i = effective interest rate or MARR per compounding period (e.g. monthly or yearly), k = index for each study period, F_k = future cash flow at the end of period k, N = number of study periods,

R = annual equivalent savings of a project, E = annual equivalent expense, CR = annual equivalent capital recovery amount, I = initial investment, $I(A/P, i\%, N)$ = annual (A) initial investment given the present value (P) at an interest rate i% per study period for N study periods, S = salvage (market) value at the end of the study period, $S(A/F, i\%, N)$ = annual (A) salvage value given the future value (F) at the interest rate i% per study period for N study periods, R_k = net revenue or savings for the kth year, E_k = net expenditure for the kth year, I = capital investment made at the present time (k = 0)

Case study: A residential building with energy piles in Melbourne

To better assess and exemplify the financial feasibility of equipping residential buildings with energy piles, a typical residential building located in Melbourne is examined. The urban area of Melbourne is of particular interest due to the soft soil conditions (mainly highly compressible silty clay) and thus most buildings would need piles for structural purposes [31,32]. To reach strong bedrock material, piles need to be placed between 15 and 25 m below the ground level. Thus, for a typical residential building built on soft soil, it is realistic to envision that eight 20-m-long piles would be required at a spacing of 4 m to support the building.

Thermal energy exchange adjustment for energy piles

GSHP systems with vertical boreholes are typically designed using software applications based on numerical, analytical, or semi-analytical methods. The most widespread method is to use the finite line source model to generate so-called G-functions, as proposed by Eskilson [33], for a given borehole configuration with an AR value over 200. This G-function provides ground temperature changes over time, which are then used to calculate the design borehole GHE length. However, for energy piles with much lower ARs, new design methods have not yet been developed. Instead, methods for vertical boreholes are typically used despite the difference in geometry (with AR values between 10 and 50 for energy piles) [20], and discrepancies have been reported as a result [34]. Especially at smaller timescales, Eskilson's G-functions would potentially underestimate temperatures for large-diameter heat exchangers such as energy piles [35]. In this paper, modified factors of the G-function proposed by Loveridge et al. [17,20] will be used to account for the reduced AR value and reduced spacing for energy piles in order to derive a realistic energy pile GSHP system design used as example. The correction is performed based on a depth-to- diameter ratio of 33 and a spacing-to-diameter ratio of 7. The first correction accounts for the effect of adjacent energy piles, and according to the chart proposed by Loveridge et al. [17], it shows a 25% increase in steady-state G-function output for the proposed energy piles. Thus, the thermal energy available for extraction for each of the eight proposed piles would be only 80% (1/1.25) of that for a single pile with no adjacent energy piles.

The second correction effectively translates the amount of energy available for extraction between a single energy pile and a single equivalent vertical borehole. As Loveridge et al. [20] illustrated in their research, such a difference would depend on the thermal properties of concrete and soil. For different concrete and soil combinations, Loveridge et al. found that the finite line source model of a single energy pile sits between the upper and lower boundaries of a numerical model of a single energy pile [20]. Therefore, it is reasonable to assume that both configurations (borehole GHEs and energy piles) would generate a similar amount of thermal energy given the same depth and ground thermal conductivity (Table 1).

Previous work on a number of monitored residential GSHP systems in Australia revealed that an average peak thermal loading of 10 kW is met by a total borehole GHE length of 120 m [4]. Given the reduction factor of 80%, a total pile length of 150 m is needed to provide an equivalent amount of thermal energy. The eight 20-m structural piles of a typical residential building in Melbourne (total 160 m) would then provide enough length to meet such thermal (and structural) demand.

Key input parameters for economic analysis

Published detailed cost and performance data of several monitored residential GSHP systems [4,5] is summaries in Table

2. These data will serve as the basis for the subsequent economic analysis (Table 2).

Table 2: Cost and performance data for monitored residential GSHP systems [4,5].

Documented GSHP Cost Data		
Item	**Price (USD)**	**Unit**
Drilling and grouting	61	per metre
Ground heat exchanger	14	per metre
Labour for installing GHE	24	per metre
Header pipe installation	2,690	per installation
Heat pump	4,940	10 kW unit
Mechanical room installation	2,330	per installation
Fittings	1,580	per installation
Documented GSHP Performance Data		
Average heating COP	3.8	
Average cooling COP	3.6	

In terms of capital cost and in the simplest way, the only difference between a borehole GSHP system and an energy pile GSHP system lies in the cost of drilling and grouting. Thus, utilizing the information shown in Table 2, a typical 10kW energy pile GSHP system would cost around $17,200, which represents a significant reduction from the capital cost of $23,300 for a typical borehole GSHP system [4,5]. In the following sections, an energy pile GSHP system will be compared against i) a reversible ASHP (Air Source Heat Pump) system and ii) a cooling only ASHP with a gas furnace. Other common HVAC systems, such as electric heaters and wood furnaces have shown to be not as financially competitive [26,36], thus they will be excluded from the comparison. A reversible ASHP system is becoming a common option for residential buildings. The advantage of such a system is its relatively low capital cost. As shown in Table 3, its capital cost is less than 40% of the capital cost for an energy pile GSHP system. ASHP systems also have high energy efficiency when compared to other conventional HVAC systems. A cooling only ASHP (air conditioning) with a gas furnace (for heating) is also quite common given the low natural gas price and extended heating period throughout the year. Gas furnaces are typically fueled by piped gas. However, in remote regions where gas pipelines are not available, Liquefied Petroleum Gas (LPG) is often used as an alternative although at a higher cost. Table 3 summarizes the key characteristics of all the systems which will be used for analysis. All other relevant parameters which are used in the analysis are listed in Table 4. The design life for the comparison is set as 20 years. This is to ensure a complete life span of each system so that calculation of the salvage value is avoided (Table 3,4).

Table 3: Characteristics of different heating/cooling systems [4].

	System 1 (GSHP)	System 2 (ASHP)	System 3a (ASHP & piped gas furnace)	System 3b (ASHP & LPG furnace)
Capital cost ($)	17,200	6,360*	6,360 + 3,150 = 9,513*	6,360 + 3,150 = 9,513*
Life span (years)	20	10	10	10
Replacement cost ($)	N/A**	6,360	6,360 + 3,150 = 9,510	6,360 + 3,150 = 9,510
Heating efficiency	3.8	3	0.92	0.92
Cooling efficiency	3.6	2.5	2.5	2.5

* The capital costs for conventional HVAC were taken from the 2015 Rawlinsons construction cost guide [37]

** For a design life of 20 years, there would be no replacement cost for a GSHP system.

Table 4: Parameters used for economic analysis [4].

Item	AU Value	Unit
Annual heating requirement	16,296	kWh
Annual cooling requirement	3,696	kWh
Electricity price	14.4	c/kWh
Natural gas price	1	c/MJ
	3.7	c/kWh
LPG gas price	10.5	c/kWh
Electricity inflation	6.2	%
Gas inflation	6.1	%
MARR*	3	%

* This MARR value is the typical interest offered by banks.

Results and Discussion: Cost-Effectiveness of Energy Piles

In this sub-section, four scenarios will be presented by comparing several combinations of the different HVAC systems listed in Table 3. These are: a) comparing an energy pile GSHP system with a reversible ASHP system, b) comparing an energy pile GSHP system with a cooling-only ASHP with a piped gas furnace, c) comparing an energy pile GSHP system with a cooling-only ASHP with an LPG furnace, and d) comparing a reversible ASHP system with a cooling-only ASHP with a piped gas furnace. Table 5 summarizes the results of all economic indicators detailed in Table 1 for the Melbourne case study. When comparing an energy pile GSHP system (System 1) with a reversible ASHP system (System 2), the former is more financially feasible. This assessment is affirmed by all the presented economic indicators. For instance, there is a net gain of $8,767 PW when using an energy pile GSHP system instead of a reversible ASHP system. This is equivalent to a yearly gain of $589 across the project's life span (20 years), which is indeed the Annual Worth (AW) value (Table 5).

Table 5: Results of different scenarios under a design life of 20 years (Australia scenario).

		PW	AW	SPP
a	GSHP against ASHP	$8,767	$589	12.6
b	GSHP against ASHP & piped gas furnace	$10,528	$708	9.7
c	GSHP against ASHP & LPG furnace	$43,046	$2,893	4.9
d	ASHP & piped gas furnace against ASHP	-($1,761)	-($118)	0

When the comparison is made between an energy pile GSHP system (System 1) and a cooling only ASHP with an LPG furnace (System 3b), the results are even more favorable towards a GSHP system. In rural Australia, LPG furnaces are a common choice for space heating as piped gas is not available. It is clear from the analysis that an LPG furnace is not a cost-effective option and a GSHP system would have the greatest potential there as an alternative. An interesting observation is the comparison between a reversible ASHP system and a cooling- only ASHP with a piped gas furnace, as is still common in urban areas. The analysis indicates that installing a piped gas furnace there provides no real benefit despite the currently low cost of piped gas at 1.0 c/MJ (3.7 c/kWh), which is only a quarter of the cost of electricity (14.4 c/kWh) in this case. Such a conclusion is contributed by the relatively low energy efficiency and high capital cost of a gas furnace. The energy efficiency of a gas furnace is normally 0.92 (although it can be as low as 0.85); thus, to provide 1 kWh of heating, the operational cost would be 4.0 cents. For an ASHP system, the energy efficiency in heating is 3; thus, to provide 1 kWh of heating, the operational cost would be 4.8 cents. Therefore, using a gas furnace would indeed save around 17% of the operational cost when compared with an ASHP system. However, the additional capital cost of a gas furnace would not justify the savings in operational cost. Note that this conclusion is based on the heating demand listed in Table 4. If more heating is required, utilizing a piped gas furnace would potentially be more economically feasible. However, the difference would not be significant.

Overall, the economic analysis suggests that investing in an energy pile GSHP system would have a significant financial return, with an annual gain ranging between around $600 and $2,900 when compared with other efficient conventional HVAC systems and much more when compared to less efficient alternatives such as wood and electric heaters. Given that the chosen conventional HVAC systems are already among the most economical options for residential space heating and cooling, the results strongly suggest that an energy pile GSHP system confers a significant economic benefit as compared to other options under a design life of 20 years. For a design life of over 20 years, a GSHP system would result in further financial benefit compared to other conventional systems. As shown in previous works [4], the only replacement cost for a GSHP system, when the design life exceeds its life span (20 years), is the cost of a heat pump (around $5,000). Thus, with a longer usage span, owners of GSHP systems would benefit more from the savings in operational cost [37-40].

Comparing an Energy Pile GSHP System with A Borehole GSHP System

It has been widely agreed that energy pile GSHP systems have lower capital cost and thus make such a configuration more financially feasible [9,13]. However, to the best of the authors' knowledge, no literature has quantified such a benefit. In this paper, it is found that the capital cost of an energy pile GSHP system for a typical residential building would cost around $17,000, representing a reduction of 26% compared to an equivalent borehole GSHP system (around $23,000). Such a reduction is contributed by the deduction of drilling cost due to the fact that the structural piles need to be drilled anyway for structural reasons. Previous work on borehole GSHP systems found that under a design life of 20 years, borehole GSHP systems are slightly less financially attractive than reversible ASHP systems. However, this is not the case for energy pile GSHP systems. Due to the reduced capital cost, the economic analysis herein indicates that energy pile GSHP systems are the most cost-effective option when compared to all other conventional HVAC systems, generating an annual return ranging between $600 and $2,900 compared to the most effective HVAC alternatives.

Conclusion

This paper analyses the financial feasibility of energy pile GSHP systems when compared with other conventional HVAC systems using various economic indicators. It was found that energy pile GSHP systems are the most cost-effective method for space heating and cooling, with an annual gain ranging between $600 and $2,900 compared to all other efficient HVAC alternatives depending on the reference system. These economic benefits could easily translate into millions when using energy pile GSHP systems in greenfield developments to accommodate the growing urban population. The better financial feasibility of energy pile GSHP systems is contributed by the reduction in drilling cost and the high energy efficiency of GSHP systems. However, other intangible benefits of energy pile GSHP systems are not factored into the analysis, such as reduced greenhouse gas emissions. In addition, the cost associated with GSHP systems is still relatively high. Thus, with wide adoption of energy pile GSHP systems, especially in regions where soft or collapsible soils exist, the capital cost of energy pile GSHP systems would be further reduced, resulting in further financial benefits. This paper provides the tools and methodology to assess other such cases around the world.

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Conflict of Interest

No conflict of interest.

References

1. Mustafa Omer (2008) Ground-source heat pumps systems and applications. Renew Sustain Energy Rev 12: 344–371.
2. PF Healy, VI Ugursal (1997) Performance and economic feasibility of ground source heat pumps in cold climate. Int J Energy Res 21: 857–870.
3. Bureau of Resources and Energy Economics (2014) Australian Energy Update, Canberra, Australia.
4. Lu Q, Narsilio GA, Aditya GR, Johnston IW (2017) Economic analysis of vertical ground source heat pump systems in Melbourne. Energy 125: 107–117.

5. Lu Q, Narsilio GA, Aditya GR, Johnston IW (2017) Cost and performance data for residential buildings fitted with GSHP systems in Melbourne Australia. Data Br. 12: 9–12.
6. Blum P, Campillo G, Kölbel T (2011) Techno-economic and spatial analysis of vertical ground source heat pump systems in Germany. Energy 36: 3002–3011.
7. Wood CJ, Liu H, Riffat SB (2010) An investigation of the heat pump performance and ground temperature of a piled foundation heat exchanger system for a residential building. Energy 35: 4932–4940.
8. Brandl H (2006) Energy foundations and other thermo-active ground structures, Géotechnique 56: 81–122.
9. Riffat SB, Wood CJ, Liu H (2009) Use of energy piles in a residential building, and effects on ground temperature and heat pump efficiency. Géotechnique 59: 287–290.
10. Ennigkeit A, Katzenbach R (2001) The double use of piles as foundations and heat exchanging elements. Soil Mech Geotech Eng pp. 893–896.
11. Bourne-Webb PJ, Amatya B, Soga K, Amis T, Davidson C, et al. (2009) Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles. Géotechnique 59: 237–248.
12. Amatya BL, Soga K, Bourne-Webb PJ, Amis T, Laloui L (2012) Thermo-mechanical behaviour of energy piles. Géotechnique 62: 503–519.
13. Hamada Y, Saitoh H, Nakamura M, Kubota H, Ochifuji K (2007) Field performance of an energy pile system for space heating. Energy Build 39: 517–524.
14. He M, Lam HN (2015) Study of geothermal seasonal cooling storage system with energy piles, Hong Kong.
15. Faizal M, Bouazza A, Singh RM (2016) Heat transfer enhancement of geothermal energy piles. Renew Sustain Energy Rev 57: 16–33.
16. Faizal M, Bouazza A, Singh RM (2016) An experimental investigation of the influence of intermittent and continuous operating modes on the thermal behaviour of a full-scale geothermal energy pile. Geomech Energy Environ 8: 8–29.
17. Loveridge F, Powrie W (2014) G-Functions for multiple interacting pile heat exchangers. Energy 64: 747–757.
18. Narsilio GA, Franco F, Ferrero H, Bidarmaghz A, Serrano C, et al. (2015) Geothermal Energy in Loess: A Detailed Numerical Case Study for Cordoba. In: Proc. XV Pan-American Conf Soil Mech Geotech Eng pp. 704-711.
19. Bidarmaghz A, X Makasis N, Narsilio GA, Francisca FM, Carro Pérez ME (2016) Geothermal energy in loess. Environ Geotech 3: 225-236.
20. Loveridge F, Powrie W (2013) Temperature response functions (G-functions) for single pile heat exchangers. Energy 57: 554-564.
21. Lund JW, Freeston DH, Boyd TL (2011) Direct utilization of geothermal energy 2010 worldwide review. Geothermics 40: 159-180.
22. Rawlings RHD, Sykulski JR (1999) Ground source heat pumps: A technology review, Build. Serv. Eng. Res. Technol. 20: 119-129.
23. European Geothermal Energy Council (2004) Financial incentives schemes for geothermal energy, Luxembourg, Europe.
24. Lund JW, Boyd TL (2016) Direct utilization of geothermal energy 2015 worldwide review. Geothermics 60: 66-93.
25. Lund JW, Freeston DH, Boyd TL (2005) Direct application of geothermal energy: 2005 Worldwide review. Geothermics 34: 691–727.
26. Self SJ, Reddy BV, Rosen MA (2013) Geothermal heat pump systems: Status review and comparison with other heating options. Appl Energy 101: 341–348.
27. Badescu V (2007) Economic aspects of using ground thermal energy for passive house heating, Renew. Energy. 32: 895–903.
28. Petit PJ, Meyer JP (1998) Economic potential of vertical ground-source heat pumps compared to air-source air conditioners in South Africa. Energy 23:137–143.
29. Shi K, Xu GJ, Shi MJ, Shen MX (2013) Economic and Technical Analysis of Substituting GSHP for Conventional Air-Conditioning System. Adv Mater Res 805-806: 620–623.
30. Nguyen HV, Law YLE, Zhou X, Walsh PR, Leong WH, et al. (2016) A techno-economic analysis of heat-pump entering fluid temperatures, and CO2 emissions for hybrid ground- source heat pump systems. Geothermics 61: 24–34.
31. William G Sullivan, Elin M Wicks (2014) Engineering economy(16th edn.) Pearson Education Limited, London, UK.
32. De Moel M, Bach PM, Bouazza A, Singh RM, Sun JO (2010) Technological advances and applications of geothermal energy pile foundations and their feasibility in Australia. Renew Sustain Energy Rev 14: 2683–2696.
33. Eskilson P (1987) Thermal Analysis of Heat Extraction Boreholes, Lund University, Sweden .
34. Wood CJ, Liu H, Riffat SB (2010) Comparison of a modelled and field-tested piled ground heat exchanger system for a residential building and the simulated effect of assisted ground heat recharge. Int J Low-Carbon Technol 5: 137–143.
35. Loveridge F, Powrie W (2013) Pile heat exchangers: thermal behaviour and interactions. Proc ICE - Geotech Eng 166: 178–196.
36. Esen H, Inalli M, Esen M (2006) Technoeconomic appraisal of a ground source heat pump system for a heating season in eastern Turkey. Energy Convers Manag 47: 1281–1297.
37. Rawlinsons Group (2015) Rawlinsons construction cost guide for housing, small commercial & industrial buildings (24th edn.) Rawlinsons Group, Perth, Australia.
38. Wang X, Chen D, Ren Z (2010) Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. Build Environ 45: 1663–1682.
39. Aebischer B, Catenazzi G, Jakob M (2007) Impact of climate change on thermal comfort, heating and cooling energy demand in Europe. ECEEE pp. 859–870.
40. Karl TR, Melillo JM, Peterson TC (2009) Global climate change impacts in the United States, USA.