Techno-economic evaluation of multiple energy piles for a ground-coupled heat pump system

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ABSTRACT

A technical and economic feasibility study of multiple energy piles (EPs) for a ground-coupled heat pump (GCHP) system is presented in this paper. The GCHP system energy performance and life-cycle cost (LCC) are evaluated, it is found that the system energy output (heating and cooling) could meet a domestic building comfortable environment requirement with the annual average COP of 3.63 and EER of 4.62. The LCC evaluation indicates that the system net present value (NPV) is approximately £26,095 at the market discount rate of 8.75% for a 20-year operating period. Moreover, the payback period of the GCHP system is approximately 4.31 years, which is sensitive to the main parameters including electricity price, capital investment and energy generation. Furthermore, the low discount rate and high energy generation are beneficial to the GCHP system with the high NPV and cash flows. The capital price of the system should be regulated to a lower level for the larger market potential.

Keywords: Ground-coupled heat pump, Energy pile, System performance, Life-cycle cost, Net present value, Payback period

1. Introduction

In recent years the dramatic concerns about climate change by using fossil fuels, and their accompanying costs, have driven governments, companies and consumers towards renewable energy resources, the European Parliament directive 2010/31/EU [1] on building energy performance has been adopted to accelerate renewable energy application in building sector. Currently, there are more than 160 million buildings over the whole of Europe which consume approximately 40% of the primary energy for

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heating, cooling and electricity [2, 3]. Decreasing the building sector primary energy consumption will make a substantial contribution towards achieving the EU's 2020, the UK's 2050 and other international CO_2 emission targets. Therefore, renewable energy technologies become more prevalent and are widely used in energy-efficient and cost-effective buildings.

1.1 Energy pile (EP) technology

One of the prevalent renewable energy sources is shallow geothermal energy, which can be used to fulfil building heating and cooling needs by ground-coupled heat pump (GCHP) system. A typical GCHP system includes three essential components: (i) a heat pump, (ii) a ground heat exchanger (GHE), and (iii) a piping network. In heating season, soil is regarded as a heat source for the GCHP system while in cooling season, it is treated as a heat sink. In terms of most regions of Europe, the seasonal soil temperature is relatively stabilized with ranging from 10 °C to 15 °C underneath a depth of 10-15 m, symbolizing good condition for heat extracted and rejected [4]. Due to the requirement of large land area for the horizontal loop and high expense for the vertical loop, the GHE pipes can be mounted inside building structural foundation elements referred as energy pile (EP) [5, 6] as presented in Fig.1.

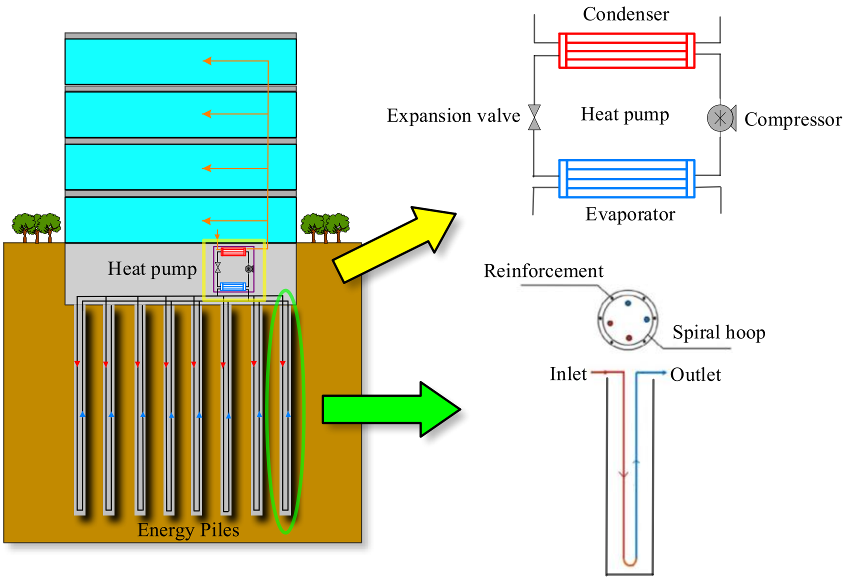


Fig.1. The schematic diagram of EPs foundation

The EP primary advantage is its dual functions as heat exchanger and building structural element. Meanwhile, concrete is utilized as an ideal heat transfer medium for heat transfer because of its high thermal energy storage capacity and thermal conductivity [7, 8]. It is found that the GCHP system with EPs can achieve energy-saving of approximately 75% in comparison to the traditional air conditioning system [9-13]. In the past decades, there are several EP systems mounted in Europe, particularly in United Kingdom, Germany, Switzerland and Austria [14]. Some case studies have been carried out including Zurich airport in Germany [15], international solar centre in Berlin [16], multi-purpose hall in Austria [17] and Keble College in Oxford [18]. In excess of three hundred foundation EPs have been installed at Dock Midfield Zurich airport [15], and the system performance evaluation reveals that about 85% of the annual heating requirement and 100% of the annual cooling need are covered by the system. International solar centre in Berlin adopted 200 EPs to cover 20% of heating and 100% of cooling requirements [16]. 320 EPs with 18 m length were installed in a multi-purpose hall with a capacity of 8,000 people in Austria for space heating and cooling, the installed system could save natural gas of 85,000 m^3 per annum, which is equivalent to a reduction of CO_2 emission of 73 tons [17]. One of the largest projects is at the Keble College Oxford, which is also the first EP structure in the UK, established in 2001 [18]. Since then, the number of mounted EPs in the UK has promptly increased, with almost 4,600 EPs (cumulative) until 2010 [19].

Recently, the performance improvement of the GCHP system with EPs has received more attentions, owing to the fact that it is one of the most effective measures for building air conditioning [20], therefore, some research works [21-24] have been implemented to study its heat transfer features. Hamada et al. [21] analysed the performance of an EP unit, and found that the unit makes up about 90% of building thermal energy requirement as well as the average heating COP is 3.9. Darkwa et al. [22] investigated a single EP performance during the long-term operating period, and concluded that the annual average thermal energy rejected into ground is about 4.5 times higher than the amount extracted. Kim et al. [23] utilized the TRNSYS software to evaluate the system performance of a GCHP with EPs, and obtained that the COP values can be increased by 25.2% and 15.1% under heating and cooling modes, respectively. Capozza et al. [24] compared the performance characteristics between a hybrid GCHP with a heat storage bath and a pure one, and discovered that the average COP of the hybrid system is approximately 7.2% higher than that of the pure one at the optimum running circumstance.

1.2 Economic evaluation

Due to their merits of the GCHP system with EPs, some studies [25-33] focus on the techno-economic assessment for various EPs categories in different regions. Most of them assess the system energy performance by various approaches, and then analyse and predict financial benefits based on different economic indicators, such as life cycle cost (LCC) [27-34], Monte Carlo method [32], Bin method [33], life cycle assessment (LCA) [35-37], discounted cash flow analysis (DCFA) [38], discounted payback period (DPB) [28], and simple payback period (SPB) [27,30]. According to these research results, it can be found for the GCHP system with EPs that: 1) its net present value (NPV) is approximately £24,000–£30,000 for a 20–25 years' service lifetime; 2) its payback period is about 4–10 years in general.

Bristow et al. [25] demonstrated the GCHP technology in Canada, and their results indicate that the technology can not only reduce CO_2 emission but also shorten the payback time. Yoon and Lee [26] studied the LCC of a GCHP at Korean Incheon International airport by one intelligent operating method to decrease the energy consumption and operating bills. Chiasson [27] analysed three air conditioning systems for an office building in Nebraska, USA, and obtained that the GCHP unit has the lowest LCC over air-source heat pump (ASHP), direct expansion (DX) cooling and gas heating units, as well as its payback period is approximately 6.5 years. Morrone et al. [28] compared the cost effectiveness between the conventional and EPs systems by using NPV and discounted payback time (DPB) methods in Naples and Milan of Italy. It is demonstrated that the cost-saving of EPs system can be achieved approximately 20% with 8-11 years' DPB in comparison to the conventional unit in Naples, while the saving is predicted no more than 10% with 4 years' DPB in Milan. Vu et al. [29] proposed an economic model to optimize the LCC of a GCHP system in view of the impact of pipe size and heat pump capacity on different U-type heat exchangers. Their results reflect that the pipe size and heat pump capacity have more effects on the coil-type GHEs than that of other U-type GHEs. Ren et al. [30] estimated energy and economic benefits of the GCHP units with both steel and polyethylene (PE) heat exchangers in China, and discovered that the investment of the steel heat exchanger and energy consumption are less than the PE one by 35.2% and 45.6%, respectively. The payback periods of the steal and PE heat exchangers reach 1.83 years and 3.45 years, respectively. Canbek [31] reported that the GCHP systems could save about 45–55% of heating and cooling expenses for residential buildings in the hot and humid climate. Zhu et al. [32] studied the LCC of a GCHP system based on the Monte Carlo method for a commercial building in USA and compared with the probabilistic method by @risk software with considering the data uncertainties. They confirmed that the GCHP unit is more favourable than the conventional system. Lu et al. [33] assessed the performances of several GCHP units and compared their costs against other traditional heating and cooling system's based on the Bin method in Melbourne, and revealed that for a design lifetime of 20 years, the ASHP is more economically attractive than the GCHP unit whereas for a design life of 40 years, the GCHP system can produce more saving than other alternatives. Arat and Arslan [34] implemented economic analysis for a GCHP system to provide district heating for a town centre with a population of about 25,000 in Turkey through the LCC method, and denoted that the system can supply enough heat for the residences in a figure between 7,929 and 46,098 along with NPV varying from US$ 1,192.81 to US$ 23.20 million.

Based on the aforementioned techno-economic assessments for the GCHP system with EPs, many studies have been implemented on energy performance and LCC analysis, the long-term performance assessment is one of the challenges to integrate the system into domestic building. Furthermore, the main obstacles in using LCC involve life of assets, erratic economic alteration, uncertainty factors concerning interest and discount rates, as well as future maintenance expense, NPV and payback period. The purpose of this paper is to assess the techno-economic characteristics of a GCHP system with EPs for a long-term operating period. The system seasonal operating performance, soil heat extracted/rejected rates, annual energy generation (heating and cooling) from the GCHP system are all determined by using the Engineering Equation Solver (EES) software. Furthermore, the system LCC assessment is carried out through the @Risk software considering the time value of the money to investigate the NPV and cumulative energy cost savings for 20 years of service lifetime. The key factors are taken into account in the complete LCC analysis, these include inflation rate, income tax rate, discount rate, interest rate, capital investment (CI), loan payment (LP), system energy cost (SEC), maintenance cost (MC), periodic cost (PC), present value (PV) of money and cumulative EP system savings (EPS). Meanwhile, the payback period is also obtained according to the values of cash flows and cumulative system energy cost (SEC) savings.

2. System description

The building selected in this study is a two-storey family house in Birmingham, UK [39, 40]. The operation period of the GCHP system with multiple EPs is from October/2007 to September/2008. Data regarding the building geometry and system parameters are obtained from the project plan and specifications [39, 40]. The diagram of EPs array layout is given in Fig.2.

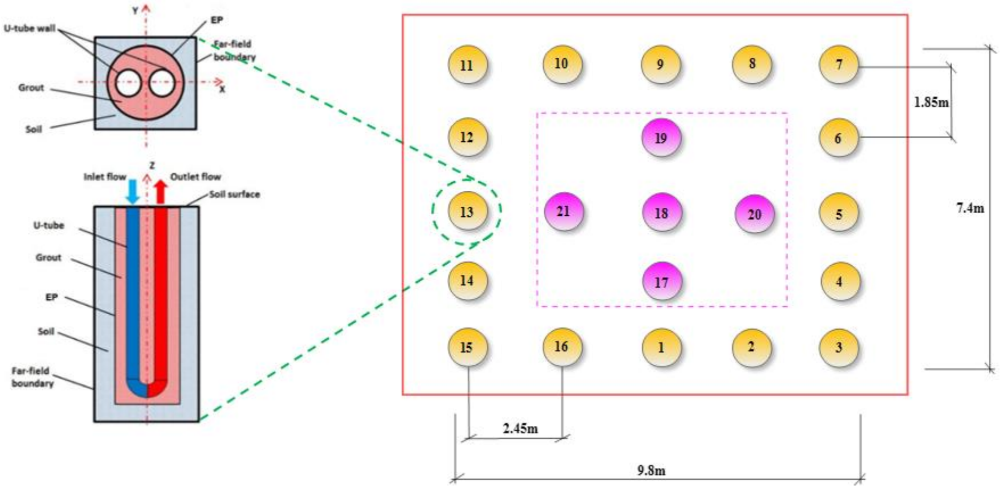


Fig.2. The diagram of multiple EPs array layout

The total number of EPs established is 21, which would be essential for the foundation demand of the family house. Nevertheless, only the perimeter 16 EPs are employed to exchange heat with ground. Each EP has a diameter of 0.3 m with 10 m depth. The U-tube is constructed with an external diameter of 0.032 m and wall thickness of 0.0029 m. The major parameters of EP are illustrated in Table 1.

Table 1 Geometrical parameters and initial conditions [39, 40]

Description	Value
Pipe external diameter	0.032 m
Pipe internal diameter	0.0262 m
EP diameter	0.3 m
Shank spacing	0.06 m
EP depth	10 m
Initial ground surface temperature	10.4 °C
Soil temperature	15.0 °C
Soil bottom temperature	15.5 °C
Fluid inlet temperature	1.2 °C

2.1 Building energy demands

The domestic building with the whole floor area of 144 m^2 is designed for one family of four people, and its mean monthly ambient temperatures and energy (heating and cooling) demands are given in Fig.3 [39]. The lowest and highest temperatures reach 4.75 °C in December and 17.38 °C in August, respectively. The maximum and minimum heating energy demands are 3,154.85 kWh and 1,372.96 kWh, respectively. On the other hand, the maximum and minimum cooling energy are 1,488.12 kWh and 862.49 kWh, respectively.

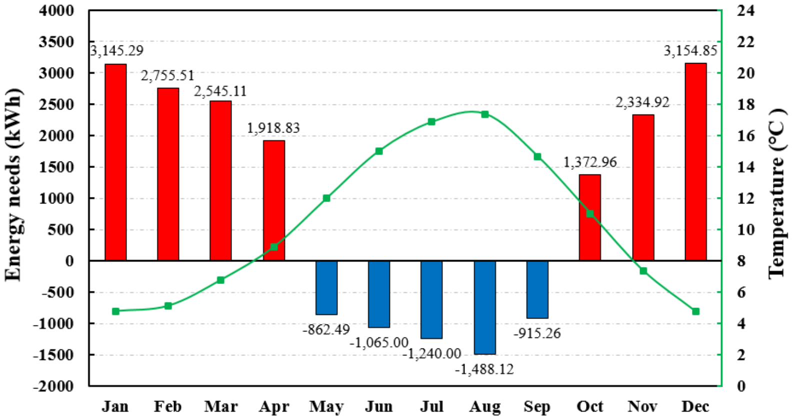


Fig.3. Monthly energy demands and ambient temperatures

2.2 Heat pump system

The EPs are linked to a 5.9 kW Greenline HT Plus heat pump [39, 40] which generates hot water at a temperature range between 35 °C and 65 °C. Technical specifications of the Greenline HT Plus [41] are given in Table 2. The main thermal property parameters are shown in Table 3.

Table 2 Nominal specifications of the heat pump [39, 41]

Description	**Value**
Emitted /Supplied output at 0/35°C	5.9/1.3 kW
Refrigerant R407C mass flow rate	0.02 kg/s
Superheat	3 °C
Subcooling	4 °C
Nominal flow heating medium	0.20 l/s
Minimum flow heating medium	0.14 l/s

Table 3 Thermal property parameters

Fluid (mixture of glycol and water)	
Density	1,035 kg/m^3
Kinematic viscosity	4.94 ×10^{-6} m^2/s
Heat capacity	3,795 J/(kg ·K)
Thermal conductivity	0.58 W/(m·K)
Pipe(High density polyethylene)	
Density	950 kg/m^3
Heat capacity	2,300 J/(kg ·K)
Thermal conductivity	0.45 W/(m ·K)
Filling (Grout)	
Density	1,860 kg/m^3
Heat capacity	840 J/(kg ·K)
Thermal conductivity	2 W/(m ·K)

Depth	Thermal conductivity	Density
Mixed Gravel and coarse sand 0 m to 2.22 m	1.30 W/(m·K)	2,277 kg/m^3

Soil	Sand gravel 2.22 m to 3.3m	1.15 W/(m·K)	2,094 kg/m^3
	Gravelly Clay 3.3m to 5.5 m	1.68 W/(m·K)	2,223 kg/m^3
	Gravelly Clay 5.5m to 10 m	1.75 W/(m·K)	2,392 kg/m^3
	Weighted mean	1.50 W/(m·K)	2,260 kg/m^3

3. Methodology

3.1 Energy analysis model

3.1.1 EP thermal energy output

The energy output of the multiple EPs unit is determined based on the local weather data and a 2D thermal resistance model as shown in Fig.4.

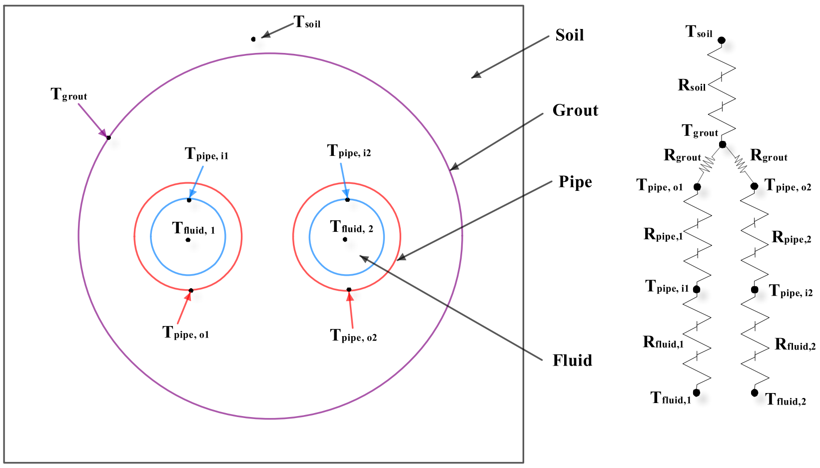


Fig.4. Cross-section of EP and corresponding thermal resistance circuit

Under the steady operating condition, the heat extracted/rejected rate from the soil (Q_{soil}) is given by [42]:

$$Q_{soil} = U \cdot A_{pipe} \cdot \Delta T_{LMTD} \tag{1}$$

where U is the total heat transfer coefficient (W/m^2·K); A_{pipe} is the surface area of the U-tube pipe (m^2); ΔT_{LMTD} is the logarithmic mean temperature difference. ΔT_{LMTD} is obtained by [42]:

$$\Delta T_{LMTD} = \frac{\left|T_{outlet} - T_{inlet}\right|}{\ln\left|\frac{(T_{outlet} - T_{soil})}{(T_{inlet} - T_{soil})}\right|} \tag{2}$$

where T_{inlet} and T_{outlet} are the inlet and outlet working fluid temperatures (°C), respectively; T_{soil} is the soil temperature (°C).

The total heat transfer coefficient can be calculated by thermal resistance equations [42]:

$$U = \frac{1}{R_{total}} \tag{3}$$

$$R_{total} = R_{fluid} + R_{pipe} + R_{grout} + R_{soil} \tag{4}$$

where R_{fluid} is the working fluid thermal resistance (K/W); R_{pipe} is the pipe thermal resistance (K/W); R_{grout} is the grout thermal resistance (K/W); R_{soil} is the soil thermal resistance (K/W).

$$R_{fluid} = \frac{1}{2\pi r_{inner} L h_{fluid}} \tag{5}$$

where r_{inner} is the internal radius of pipe (m); L is the EP length (m); h_{fluid} is the convective heat transfer coefficients of the working fluid within pipe (W/m·K).

Based on the Gnielinski correlation, the convective heat transfer coefficient is given as:

$$h_{fluid} = \frac{Nu_{D_H} \cdot \lambda_{fluid}}{2r_{inner}} \tag{6}$$

where λ_{fluid} is the thermal conductivity of the working fluid (W/m^2·K).

The Nusselt number is given as [43]:

$$Nu_{D_H} = \frac{(f/8) \times (Re_{D_h} - 1000) \times Pr}{1 + 12.7 \times \sqrt{(f/8)} \times (Pr^{2/3} - 1)} \tag{7}$$

where f is the Dracy friction factor; Re and Pr are the working fluid Reynolds and Prandtl numbers, respectively.

The Dracy friction factor is given by [43]:

$$f = [0.790 \times \ln(Re_{D_h}) - 1.64]^{-2} \tag{8}$$

Re and Pr are written as:

$$Re_{D_H} = \frac{\rho_{fluid} \upsilon_{fluid} D_H}{\mu_{fluid}} \tag{9}$$

$$Pr = \frac{c_{fluid} \mu_{fluid}}{\lambda_{fluid}} \tag{10}$$

where ρ_{fluid} is the working fluid density (kg/m^3); υ_{fluid} is the working fluid velocity (m^2/s); μ_{fluid} is the working fluid dynamic viscosity (Pa·s); D_H is the hydraulic dimeter (m).

$$R_{pipe} = \frac{1}{2\pi L \lambda_{pipe}} \ln \frac{r_{outer}}{r_{inner}} \tag{11}$$

where λ_{pipe} is the thermal conductivity of the pipe material (W/m^2·K); r_{outer} is the pipe outer radius (m).

R_{grout} is given by [44, 45]

$$R_{grout} = \frac{1}{2\pi L \lambda_{grout}} \ln \frac{r_{EP}}{r_{outer} \cdot \sqrt{\zeta}} \tag{12}$$

where λ_{grout} is the thermal conductivity of the grout (W/m^2·K); r_{EP} is the radius of EP (m); ζ is the pipe number in the EP (e.g. for a single U-tube pipe where there are two pipes in the borehole, ζ = 2).

R_{soil} is written by [44, 45]

$$R_{soil} = \frac{1}{2\pi L\lambda_{soil}} \ln \frac{r_{soil}}{r_{grout}} \tag{13}$$

where λ_{soil} is the soil thermal conductivity ($W/m^2\cdot K$); r_{soil} is the soil region radius (m); r_{grout} is the grout radius (m).

3.1.2 Heat pump power consumption

A parametric model is adopted to calculate the compressor power consumption with consideration of the influence of its rotation speed by [46]:

$$m_r = V_c\omega\rho_{r,suc} \cdot [1 + C_v(1 - \frac{P_{r,cond}}{P_{r,evap}})^{\frac{1}{n}}] \tag{14}$$

$$\Delta\xi_{comp} = \xi_{r,dis} - \xi_{r,suc} = \frac{n}{n-1} \cdot \frac{P_{r,evap}}{\rho_{r,suc}} \cdot [(\frac{P_{r,cond}}{P_{r,evap}})^{\frac{n-1}{n}} - 1] \tag{15}$$

$$W_{comp} = \frac{m_r \Delta h_{comp}}{\eta_{comp}} \tag{16}$$

where m_r is the compressor refrigerant mass flow rate (kg/s); V_c is the compressor suction volume (m^3); ω is the compressor rotational speed (rev/s); $\rho_{r,suc}$ is the compressor suction refrigerant density (kg/m^3); C_v is the compressor volumetric coefficient, P is the pressure (kPa); ξ is the specific enthalpy (kJ/kg), n is the polytropic compression coefficient; η_{comp} is the compressor mechanical efficiency; $\Delta\xi$ is the specific enthalpy change (kJ/kg); W_{comp} is the compressor power consumption (kW).

On the other hand, a circulation pump is used to keep the working fluid flowing in the EPs, its electricity consumption is added to the total energy usage of the GCHP system. The pressure drop in the EPs is calculated by using the friction factor in the Darcy Weisbach equation [47], and can be given as:

$$\Delta p = f\frac{L}{D_H}\frac{\rho_{fluid}V^2}{2} \tag{17}$$

where V is the working fluid velocity in the EPs (m/s).

The power required by the circulation pump can be calculated as:

$$W_{pump} = \frac{\Delta p \times m}{\rho_{fluid}\eta / 100} \tag{18}$$

where η is the pump efficiency (%); m is the mass flow rate in the EPs (kg/s). The fan power consumption in the air duct network is very lower compared with the compressor's or circulation pump's, so it is not considered in this study.

3.1.3 System performance

The system energy output includes the useful heating (Q_h) and cooling energy (Q_c). In heating mode, Q_h is equal to ($Q_{soil} + W_{comp} + W_{pump}$) whereas in cooling mode, Q_c is equal to ($Q_{soil} - W_{comp} - W_{pump}$). Furthermore, the key parameters to assess heat pump performance are the Coefficient of Performance (COP) in heating mode, and the Energy Efficiency Ratio (EER) in cooling mode, which are given as:

$$\mathrm{COP}=\frac{Q_h}{W}=\frac{Q_{soil}+W_{comp}+W_{pump}}{W_{comp}+W_{pump}} \tag{19}$$

$$\mathrm{EER}=\frac{Q_c}{W}=\frac{Q_{soil}-W_{comp}-W_{pump}}{W_{comp}+W_{pump}} \tag{20}$$

3.2 Economic analysis model

The LCC is the sum of all expenses associated with an energy delivery system over a selected period or its service lifetime, with consideration of the time value of money. In the LCC, the expected future expenses are brought back to the present costs (discounted) through calculating how much have to be invested at a market discount rate. The LCC assessment process can be applied to evaluate financial benefit of the GCHP system with EPs, the main parameters, for example, interest rate, income tax rate, capital investment (CI), loan payment (LP), system energy cost (SEC), maintenance cost (MC), periodic cost (PC), extra property tax (EPT), incoming tax savings (ITS), net present value (NPV) of money and cumulative EP system savings (EPS), are all evaluated in the LCC analysis. The LCC assessment of the GCHP system consists of seven parts: SEC, CI, LP, MC, PC, ITS and NPV, while the core part is the NPV calculation which is utilised to compare cash flows at different time intervals. The structure of the LCC assessment is shown in Fig.5.

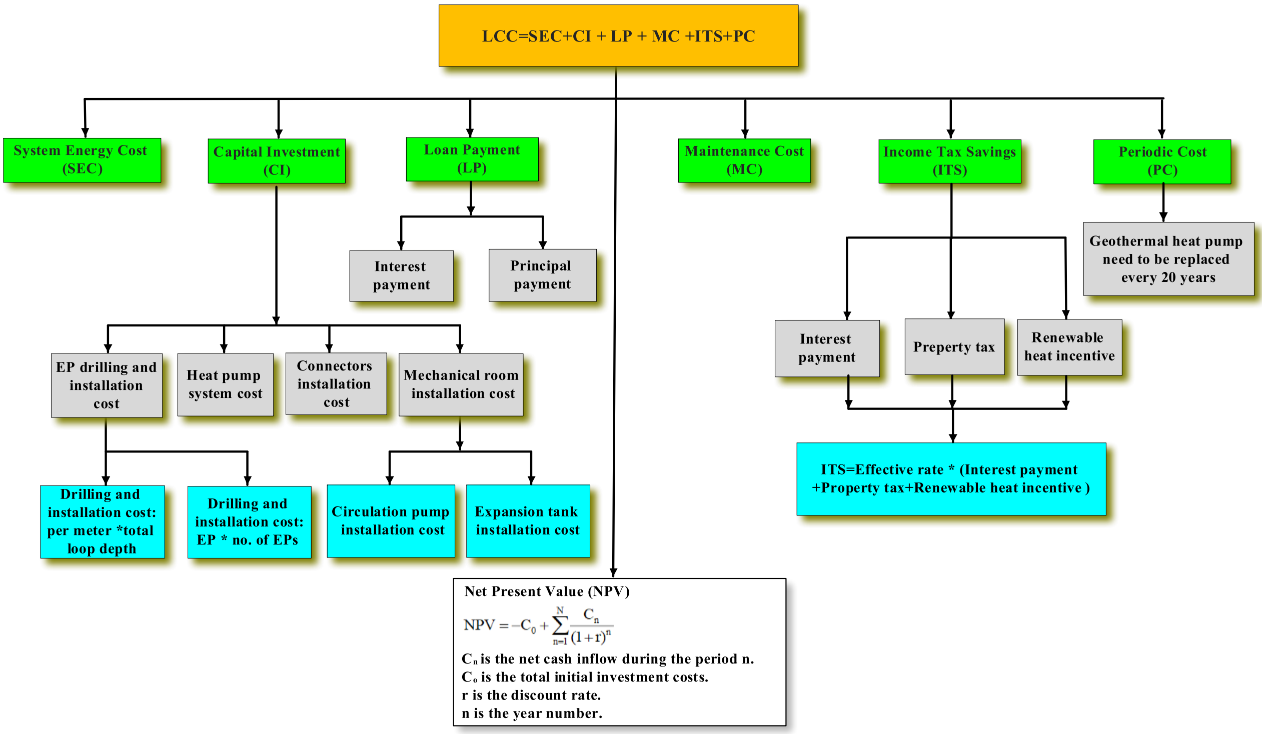


Fig.5. The LCC structure for GCHP with EPs

3.2.1 LCC analysis

According to the international standard of Environmental management BS ISO 15686 [48], the LCC refers to the systematic economic assessment of combined MC, CI, LP, SEC, PC and end-of-life costs of construction project during the whole life cycle period.

The LCC on the basis of the NPV for the GCHP system can be written as:

$$\mathrm{LCC} = \mathrm{C_{SEC}} + \mathrm{C_{CI}} + \mathrm{C_{LP}} + \mathrm{C_{MC}} + \mathrm{C_{ITS}} + \mathrm{C_{PC}} \tag{21}$$

where LCC is the GCHP system entire life cycle cost in NPV (£); C_{SEC} is the GCHP system energy cost in PV (£); C_{CI} is the GCHP system capital costs including the construction and engineering design expenses (£). In this study, only the construction expenses (installation and equipment expenses) are taken into account; C_{LP} is the annual loan payment in PV (£); C_{MC} is the GCHP system maintenance cost in PV (£); C_{ITS} is the GCHP system income tax savings expense in PV (£); C_{PC} is the GCHP system periodic cost in PV (£).

3.2.1.1 System boundary

To obtain the precise LCC assessment results and provide the strongest protection for final evaluation, the foremost thing is to determine system boundary including its scope and lifetime. The scope of the GCHP system composes of high density polyethylene U-tube pipes, EPs, heat pump unit, fan coils and circulating pumps. According to the studies [40, 41, 48], the lifetime of the polyethylene U-tube pipe is approximately 50 years. On the other hand, the service lifetime of the heat pump system could be approximately 20 years. Thereby, the 20 years' service lifetime of the GCHP system is adopted for the LCC evaluation.

3.2.1.2 System energy cost (SEC)

The SEC is also known as the fuel cost saving which is determined based on the electricity price and consumption. The electricity consumption of the system depends on heating and cooling loads of the building. The annual SEC is given as:

$$\mathrm{C_{SEC}} = \mathrm{c_{SEC}} \times \frac{1}{(1+\mathrm{d_{SEC}})^{\mathrm{N}}} \tag{22}$$

$$\mathrm{c_{SEC}} = \mathrm{E}_{\mathrm{generation}} \cdot \beta \tag{23}$$

where C_{SEC} is the GCHP system energy cost in PV (£); c_{SEC} is the GCHP annual electricity cost (£); d_{SEC} is the inflation rate of electricity price (%); N is the period of economic assessment; $E_{generation}$ is the energy generation (heating and cooling) from the GCHP system (kWh); β is the electricity price (£/kWh).

3.2.1.3 Capital investment (CI)

The high expenses of the system are for drilling and high density polyethylene pipe material, then followed by the heat pump with a mean cost of £5,600 for a capacity of 5.9 kW [41]. The other costs are comparatively low, for instance, the expenses of installing header pipes, circulation pump and expansion tank, and fittings [28].

The CI model is established based on three cost categories as follows:

$$\mathrm{CI} = \mathrm{C}_{\mathrm{ic}} + \mathrm{C}_{\mathrm{in}} + \mathrm{C}_{\mathrm{co}} \tag{24}$$

where C_{ic} is the initial expense of main equipment (£); C_{in} is the installation expense, labour expense, auxiliary equipment expense (£); C_{co} is the commissioning or subscription expense (£).

3.2.1.4 Loan payment (LP)

The LP is also referred to as the mortgage payment per annum which involves principle and interest payments to install the system.

The PV of LP is given by:

$$\mathrm{C}_{\mathrm{LP}} = \mathrm{G} \cdot \frac{\mathrm{r}_{\mathrm{LP}} \cdot (1+\mathrm{r}_{\mathrm{LP}})^{z}}{(1+\mathrm{r}_{\mathrm{LP}})^{z} - 1} \tag{25}$$

where C_{LP} is the loan payment per annum (£); G is the principal payment (£); r_{LP} is the yearly interest rate (%); z is the number of loan payment years.

3.2.1.5 Maintenance cost (MC)

The annual MC includes expected and unexpected budgets that are associated with the repair and corrective maintenance of the system. The present worth of MC per annum is given by:

$$\mathrm{C}_{\mathrm{MC}} = \mathrm{c}_{\mathrm{MC}} \times \frac{1}{(1+\mathrm{d}_{\mathrm{MC}})^{k}} \tag{26}$$

where C_{MC} is the present worth of the k^{th} year GCHP maintenance expense (£); c_{MC} is the first year maintenance expense of GCHP (£); d_{MC} is the inflation rate of maintenance (%); k is the period of maintenance payment.

3.2.1.6 Periodic cost (PC)

The PC denotes the replacement cost of main system parts. For the GCHP system, only the heat pump is required to be replaced every 20 years [41, 49, 50]. Therefore, the PC in PV is written as:

$$\mathrm{C}_{\mathrm{PC}} = \mathrm{c}_{\mathrm{PC}} \times \frac{1}{(1+\mathrm{d}_{\mathrm{PC}})^{s}} \tag{27}$$

where C_{PC} is the present worth of the s^{th} year GHCP system periodic expense (£); c_{PC} is the first year GCHP system periodic expense (£); d_{PC} is the inflation rate of replacement (%); s is the year number of periodic payment.

In fact, the PC of the GCHP system is not considered in this study because the heat pump only needs to be replaced every 20 years.

3.2.1.7 EP system savings (EPS) and income tax savings (ITS)

The EPS is also referred to as the yearly net cash flow and can be written as [49, 50]:

$$C_{EPS} = C_{SEC} - C_{LP} - C_{MC} - C_{PC} - C_{EPT} + C_{ITS} \tag{28}$$

where C_{EPT} is the extra property tax (£); C_{ITS} is the income tax savings (£).

The C_{EPT} in PV is expressed as:

$$C_{EPT} = c_{EPT} \times \frac{1}{(1+\gamma_{EPT})^{\alpha}} \tag{29}$$

where c_{EPT} is the annual extra property tax cost of the GCHP system (£); γ_{EPT} is the inflation rate of extra property tax (%); α is the period of extra property tax.

The C_{ITS} in PV is given by [49, 50]:

$$C_{ITS} = C_{ETR} \times (C_{IP} + C_{EPT} + C_{RHI}) \tag{30}$$

where C_{ETR} is the effective tax rate (%); C_{IP} is the interest payment (£); C_{RHI} is the renewable heat incentive bonus for heat generation in the UK (£).

3.2.1.8 Net present value (NPV)

The NPV is estimated to evaluate the whole gain of the system. If a payment repeats every year at an inflate rate of r per annum, the NPV is written by the following equation:

$$NPV = -C_{CI} + \sum_{N=1}^{N'} \frac{C_N}{(1+r)^N} \tag{31}$$

where C_N is the net cash inflow during the N period (£); C_{CI} is the entire capital investment expense (£); r is the discount rate (%).

A positive NPV demonstrates that the projected earning created by a project or investment surpasses the expected cost. Generally, an investment with a positive NPV will be profitable, and an investment with a negative NPV will cause a net loss.

3.3 LCC simulation process

The implementation of the LCC is done by the @Risk software, which is coupled with Microsoft Excel. The whole analysis is split into six parts and the LCC assessment flowchart is shown in Fig.6. Some critical parameters and economic equations are needed, such as the system scope, system functional component, CI value, building heating/cooling loads, heat pump specifications and number of iterations for each step. The C_{SEC}, C_{LP}, C_{MC}, C_{EPS}, C_{EPT} and C_{ITS} are obtained by using Eqs. (22), (23), (25), (26) and (28) - (30). And then, the NPV and payback period are defined as the output parameters. Meanwhile, the input parameter distribution is defined by using the Normal function. Specifically, the ranges of the capital cost, energy generation and electricity price are from £6,500 to £15,000, 13,000 kWh to 24,000 kWh, and £0.075/kWh to £0.22/kWh, respectively. In the following, the number of iteration is set as 6000 in this simulation process. Once the programmed cycles of iterations are finished, the NPV and payback period are obtained.

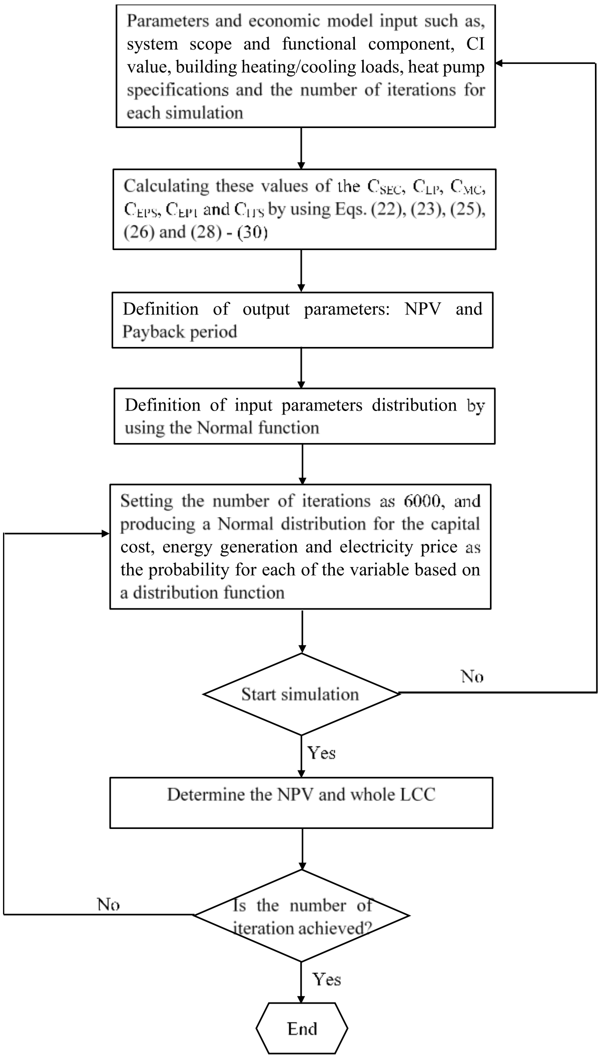


Fig.6. The flowchart of LCC assessment for GCHP with EPs

4. Results and discussion

Before the 2D numerical model is employed to simulate the system energy performance, the model validation is implemented by comparing numerical results with the experimental data [39, 40]. The COPs of the numerical and experimental results are presented in Fig.7 (a), and it is found that the maximum COP difference between them is approximately 8.33 % noticed in November. Likewise, the EERs of the numerical and experimental data are displayed in Fig.7 (b), and the maximum EER difference is about 8.17 % noticed in May. Therefore, the simulation results are effectively supported by the experimental data, so the 2D numerical model can be utilized to study the energy performance of the GSHP with multiple EPs.

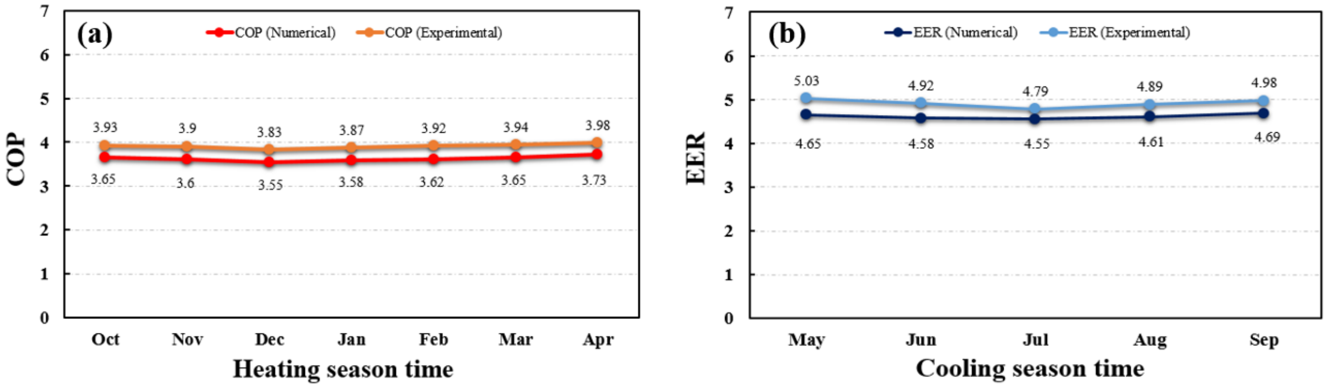


Fig.7. Comparisons between numerical results and experimental data: (a) COP; (b) EER

4.1 Energy performance

The annual operating process of the GCHP system is classified into two periods on the basis of the local climate condition. One is the heating season from October/2007 to April/2008. Another is the cooling season from May/2008 to September/2008. The mean system energy output from the heat pump (heating and cooling) and ground energy obtained (extracted and rejected) are simulated and given in Fig. 8. In this figure, the monthly thermal energy generations are lower in October and April. It is noteworthy that the minimum monthly energy output of the GCHP system is approximately 1,593.94 kWh in April whereas the maximum value is approximately 2,285.24 kWh in December. Moreover, from February to April, the GCHP system operates in most of time, therefore the soil has no enough time to recover. So the soil temperature nearby the EP is comparatively low, which results in a low temperature working fluid temperature entering into the evaporator of the heat pump unit, correspondingly a low COP. Meanwhile, the minimum value of monthly heat extracted from the ground is about 1,148.99 kWh in April, and the maximum value is about 1,890.20 kWh in December. The minimum GCHP system cooling output is about 1,000.25 kWh in September whereas the maximum value is about 1,521.78 kWh in July. Furthermore, the monthly heat rejected into the soil is also depicted, the minimum rejected heat is about 894.85 kWh in September whereas the maximum value is about 1,279.01 kWh in July.

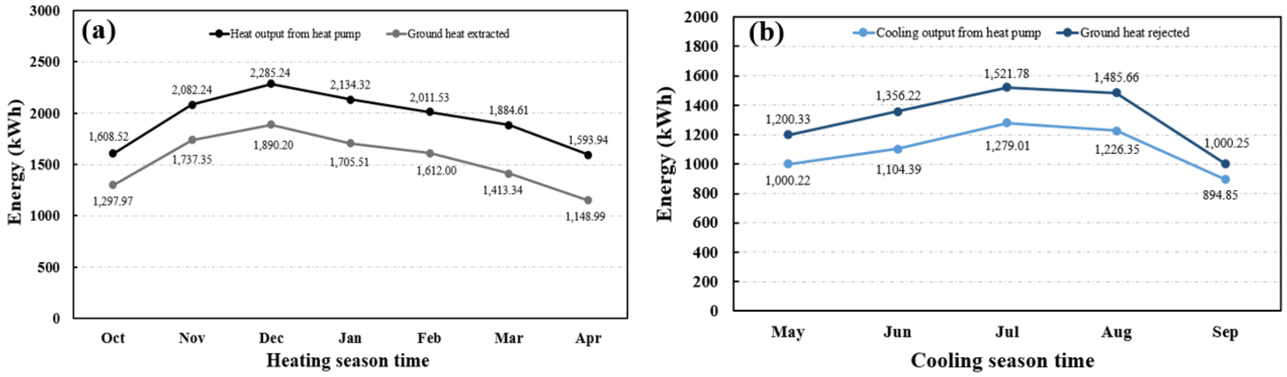


Fig.8. Energy output: (a) in the heating season; (b) in the cooling season

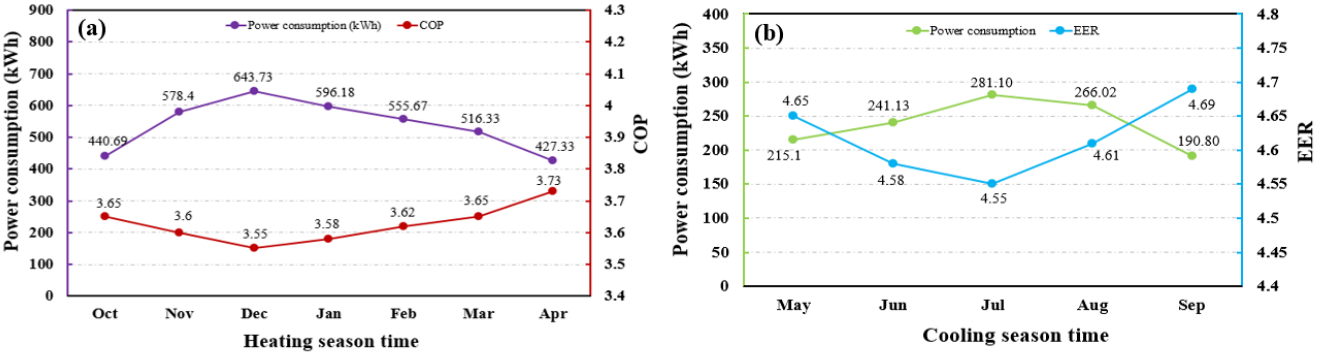


Fig.9. Electrical energy consumption and system performance: (a) in the heating season; (b) in the cooling season

The monthly electrical energy consumption and system performance in the heating and cooling seasons are shown in Fig.9. The system can fulfil the building energy demands under both operating conditions. The monthly heating electrical energy consumptions of the GCHP system are 440.69 kWh, 578.40 kWh, 643.73 kWh, 596.18 kWh, 555.67 kWh, 516.33 kWh and 427.33 kWh from October to April, with corresponding average monthly COPs reach 3.65, 3.6, 3.55, 3.58, 3.62, 3.65 and 3.73, respectively. Therefore, the system annual average COP is 3.63. The monthly cooling electrical energy consumptions are 215.10 kWh, 241.13kWh, 281.10 kWh, 266.02 kWh and 190.80 kWh from May to September, with corresponding average monthly EERs achieve 4.65, 4.58, 4.55, 4.61 and 4.69, respectively. So the system annual average EER is 4.62.

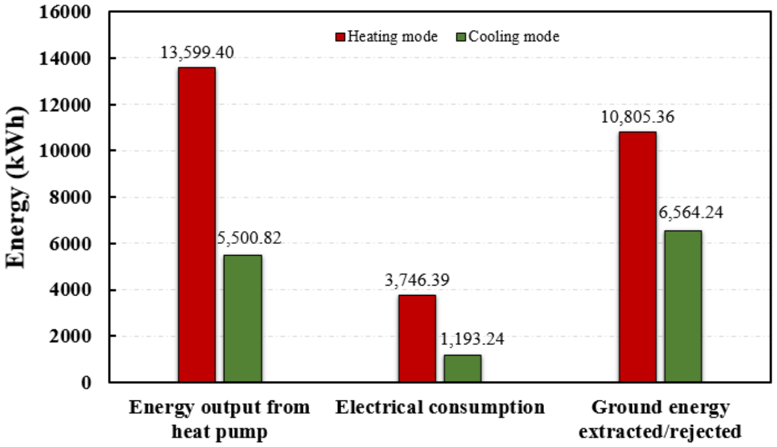


Fig.10. Annual total energy generation, electrical energy consumption and ground energy extracted/rejected

According to Fig.10, the total heat output of the GCHP system is approximately 13,599.40 kWh and the heat extracted from soil is about 10,805.36 kWh, leading to the power consumption of around 3,746.39 kWh. By comparison, the cooling output is around 5,500.82 kWh and the heat rejected into the soil is approximately 6,564.24 kWh, resulting in 1,193.24 kWh of the power consumption. Therefore, the annual energy output (heating and cooling) of the GCHP system is estimated to be about 19,100 kWh and the total power consumption reaches approximately 4,939.63 kWh. So the energy provided by the GCHP system can cover the building heating and cooling requirements.

4.2 Economic assessment

The total system capital cost is £9,033 with 10% down payment, the remaining part of the initial expense is financed at an interest rate of 8.2% for the 20 years' period. It is anticipated to pay normal maintenance expense for the system annually with an inflation rate of 4.5% [50]. Energy pricing mechanism in the UK is a combination of regulated and market-driven prices [30]. The electricity price is £0.1097/kWh by the UK government [51]. In the light of UK energy prices regulated via Ofgem [52], the RHI rate for the units between 4 kW and 10 kW is £0.1986/kWh. The property tax is 2% of the initial cost. The maintenance expense for EPs is estimated to be £150 per annum. The average effective income tax rate is evaluated to be 20% over the service lifetime period. The costs of EPs include the auger drilling, high density polyethylene pipe material, installation and maintenance costs, are given in Table 4. Details of the component prices, economic expenses and parameters are illustrated in Table 5.

Table 4 Cost breakdown of GCHP system [39]

Item	Value
EP pipe	
Pipe drilling cost	£2.63/m × 413m
Loop installation into pile reinforcement cages	£640
Estimated pipe installation cost	£1,726
Heat pump system	
Heat pump & commissioning	£5,600
Working fluid cost	£174
Estimated heat pump unit cost	£5,774
Other equipment installation	
Header circuit insulation	£186
Brass fittings	£386
4 port brass manifold with flow control	£361
Estimated other equipment cost	£933
Labour cost	
Header circuit labour	£600
Total capital cost	£9,033
Estimated maintenance cost	£150

Table 5 Parameters used for economic analysis

Item	Value
Electricity price	£0.1097/kWh
RHI for GCHP	£0.1986/kWh
Down payment	10%
Inflation rate of electricity price	6%
Interest rate of principal	8.2%
Inflation rate of maintenance	4.5%
Council rate for property tax	2%
Inflation rate of extra property tax	4%
Income tax rate	20%
UK discount rate	8.75%

The annual progressions of SEC and MC of the GCHP system for the 20-year operating period are presented in Table 6. The system annual fuel saving bill is the previous year's expense multiplied by inflation rate of electricity price. Specifically, the

SEC for the first year is approximately £2,095.27 (19,100 kWh × £0.1097/kWh) and the second year's SEC is about £2,220.99 [19,100 kWh × £0.1097/kWh × (1+6%)] with considering the inflation rate of electricity price. By the end of the 20th year, the value can reach £6,339.45 [19,100 kWh × £0.1097/kWh × $(1+6\%)^{19}$]. Similarly, the MC in the first year and 20th year achieve £150 and £346.18, respectively. Moreover, the annual progressions of LP, interest payment, remaining principal, EPS and ITS are also shown in Table 6. For example, the interest payment in the first year is £666.64 (8.2% × £8,129.7). The LP is approximately £840.39 by using Eq. (25), thereby the principal payment and remaining principal reach £173.75 (£840.39 - £666.64) and £7,955.95 (£9,033×10% - £173.75), respectively. In terms of the ITS and EPS, the progressions of the ITS and EPS for the 20-year operating period are given in columns 10 and 11, to be more specific, the ITS for the first year and 20th year are approximately £928.11 and £847.51, respectively. Moreover, the EPS for each year is the sum of the items including SEC, LP, MC, EPT and ITS. The annual EPS is brought to present worth using the UK market discount rate of 8.75%. The deposit charge is £903.3 which is a negative present value, and it is displayed as Year 0. The EPS becomes a positive value reaching approximately £1,852.33 after the first year and the EPS achieves £5,619.77 until the 20th year. Furthermore, the NPV of the GCHP system is obtained approximately £26,095.14 at the market discount rate of 8.75% for a 20-year operating period. The economic assessment demonstrates that the cash flow turns positive at the end of the first year and maintains positive permanently by the end of the service lifetime. This is because the replacement of the heat pump is only considered in the 20th year, meanwhile, the original and maintenance expenses of the GCHP system are much less as well in this case.

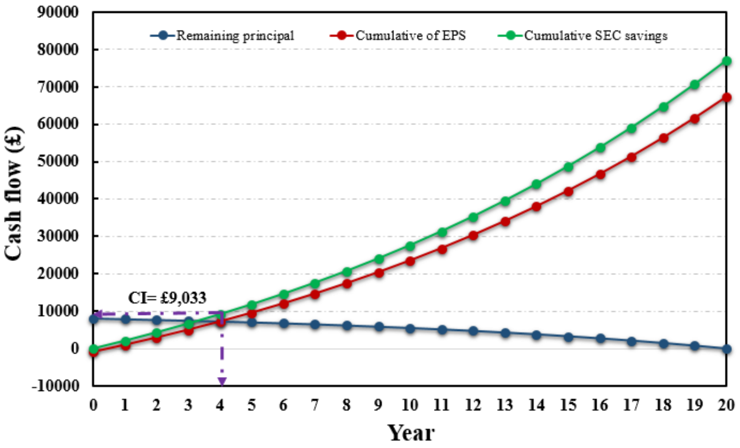


Fig.11. Variation of remaining principal, cumulative EPS and cumulative SEC savings

According to Fig.11, the cumulative SEC saving (£9,166) exceeds the CI (£9,033) by the end of the fourth year. The cumulative EPS becomes positive after one year due to the low capital and little maintenance costs. The cumulative system saving (£9,531.53) surpasses the remaining principal balance (£7,106.28) by the end of the fifth year. The calculation process of the LCC analysis is given in Table 6. Meanwhile, the payback period is approximately 4.3 years as shown in Fig.11. This is deemed an acceptable payback period (<10 years) for an engineering project of this nature, and serves to demonstrate the clear benefit of adopting such a system in the UK context.

Table 6 The economic assessment of the GCHP with multiple EPs system for Birmingham, UK (20-year service lifetime)

Year	**Energy generation (kWh/year)**	**SEC (£)**	**LP (£)**	**Interest payment (£)**	**Principal payment (£)**	**Remaining principal (£)**	**MC (£)**	**EPT (£)**	**ITS (£)**	**EPS (£)**	**Present worth of EPS (£)**	**Cumulative EPS (£)**	**Cumulative SEC savings (£)**
0						8,192.70				(903.30)	(903.30)	(903.30)	
1	19,100	2,095.27	(840.39)	666.64	173.75	7,955.95	(150)	(180.66)	928.11	1,852.33	1,703.29	949.03	2,095.27
2	19,100	2,220.99	(840.39)	652.39	188.00	7,767.94	(156.75)	(187.89)	926.70	1,962.67	1,659.54	2,911.69	4,316.26
3	19,100	2,354.25	(840.39)	636.97	203.42	7,564.52	(163.80)	(195.40)	925.13	2,079.78	1,617.07	4,991.47	6,670.50
4	19,100	2,495.50	(840.39)	620.29	220.10	7,344.43	(171.18)	(203.22)	923.35	2,204.07	1,575.83	7,195.55	9,166.00
5	19,100	2,645.23	(840.39)	602.24	238.15	7,106.28	(178.88)	(211.35)	921.37	2,335.99	1,535.76	9,531.53	11,811.23
6	19,100	2,803.94	(840.39)	582.71	257.68	6,848.60	(186.93)	(219.80)	919.16	2,475.98	1,496.83	12,007.51	14,615.18
7	19,100	2,972.18	(840.39)	561.59	278.80	6,569.80	(195.34)	(228.59)	916.69	2,624.55	1,458.98	14,632.06	17,587.36
8	19,100	3,150.51	(840.39)	538.72	301.67	6,268.13	(204.13)	(237.74)	913.94	2,782.19	1,422.18	17,414.26	20,737.87
9	19,100	3,339.54	(840.39)	513.99	326.40	5,941.73	(213.32)	(247.25)	910.89	2,949.49	1,386.38	20,363.75	24,077.41
10	19,100	3,539.92	(840.39)	487.22	353.17	5,588.56	(222.91)	(257.14)	907.52	3,126.99	1,351.56	23,490.75	27,617.32
11	19,100	3,752.31	(840.39)	458.26	382.13	5,206.43	(232.95)	(267.42)	903.79	3,315.34	1,317.67	26,806.09	31,369.63
12	19,100	3,977.45	(840.39)	426.93	413.46	4,792.97	(243.43)	(278.12)	899.66	3,515.17	1,284.68	30,321.26	35,347.08
13	19,100	4,216.10	(840.39)	393.02	447.37	4,345.60	(254.38)	(289.24)	895.11	3,727.19	1,252.57	34,048.45	39,563.18
14	19,100	4,469.06	(840.39)	356.34	484.05	3,861.55	(265.83)	(300.81)	890.08	3,952.11	1,221.29	38,000.56	44,032.24
15	19,100	4,737.20	(840.39)	316.65	523.74	3,337.81	(277.79)	(312.84)	884.55	4,190.73	1,190.83	42,191.29	48,769.44
16	19,100	5,021.44	(840.39)	273.70	566.69	2,771.12	(290.29)	(325.36)	878.46	4,443.86	1,161.16	46,635.15	53,790.88
17	19,100	5,322.72	(840.39)	227.23	613.16	2,157.96	(303.36)	(338.37)	871.77	4,712.38	1,132.25	51,347.52	59,113.60
18	19,100	5,642.09	(840.39)	176.95	663.44	1,494.53	(317.01)	(351.91)	864.42	4,997.21	1,104.08	56,344.73	64,755.69
19	19,100	5,980.61	(840.39)	122.55	717.84	776.69	(331.27)	(365.98)	856.36	5,299.32	1,076.63	61,644.05	70,736.30
20	19,100	6,339.45	(840.39)	63.69	776.70	-0.015	(346.18)	(380.62)	847.51	5,619.77	1,049.86	67,263.82	77,075.75
Total											**26,095.14**		

4.3 Sensitive analyses of NPV and payback period

In the following, the comparison analyses are implemented with respect to the NPV and payback period with different parameters. The distribution graphs of cumulative probability versus NPV and payback time for the GCHP system over the whole LCC period are presented in Figs.12 and 13 respectively. The legend gives the minimum, maximum, average, number of iterations and standard deviation of NPV and payback period in this case.

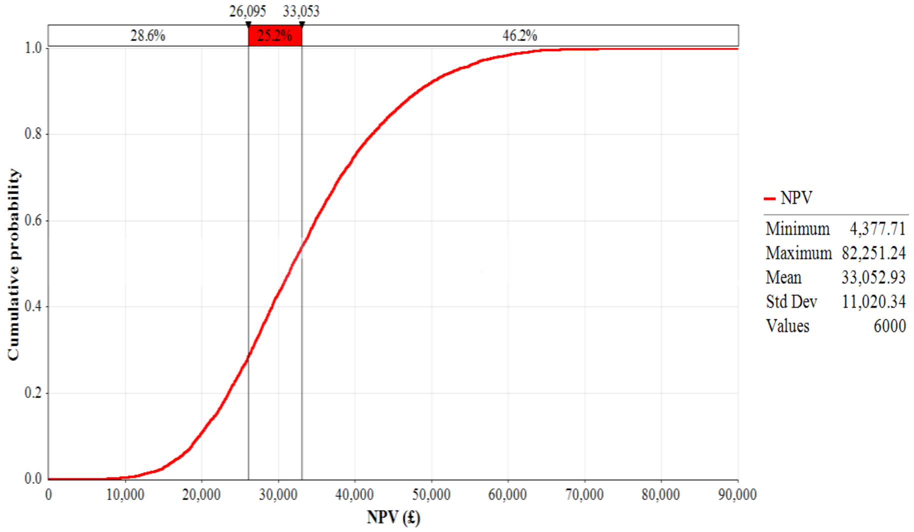


Fig.12. NPV distribution

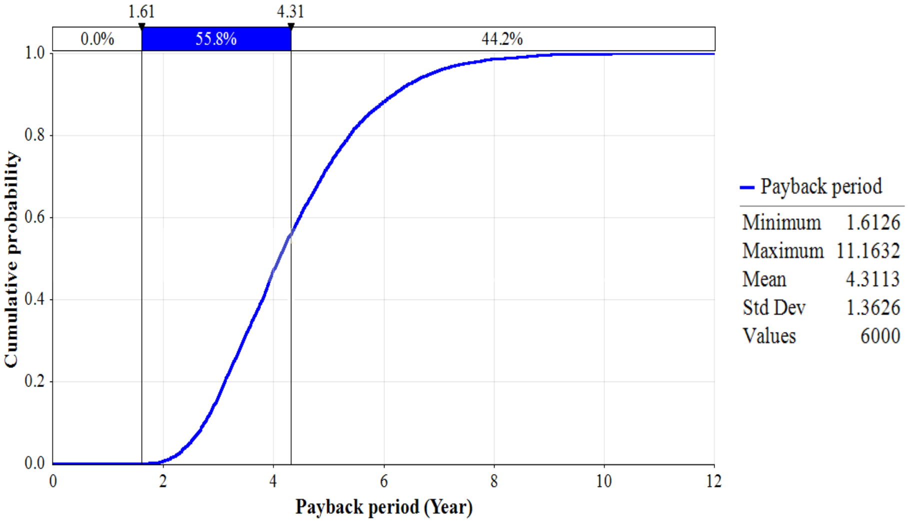


Fig.13. Payback period distribution

The vertical lines in Fig.12 represent the NPV of present case (£26,095) and average value (£33,053). One row of percentages on the top of the diagram displays the probabilities relative to the NPV. Specifically, the top row depicts the probability regarding the LCC of the GCHP system which is classified into three categories. When the NPV is less than the present case value, it accounts for 28.6%; when the NPV is located between the NPV of the present case value and average value, it makes up 25.2%; when the NPV is greater than the average value, it accounts for a proportion of 46.2%. By comparison, the vertical lines in Fig.12

denote the minimum and average values in the payback period. Based on one row of percentages on the top of the graph, there is a probability of 44.2% that the payback period of the system is more than 4.31 years, and 55.8% of the payback time is between 1.61 and 4.31 years, while 0% of the payback period is less than 1.61 years.

4.3.1 NPV variation with the uncertain input factors

The NPV variations with the uncertain input factors are shown in Fig.14. It is denoted that the uncertainty associated with electricity price has the largest effect on the NPV whereas the inflation rate of maintenance cost has the least impact among the uncertain input parameters. Notably, the low electricity price makes the NPV to be £20,308.66, 38.6% lower compared to the baseline of £33,068.19. On the contrary, the high electricity price makes the NPV as high as £49,255.99 (50.0% higher). Similarly, the uncertainty in energy generation is closely related to the variety of financial credits achieved from improving the NPV. Thus, the range of energy generation by using the GCHP system results in a NPV variation of approximately £23,078.62 - £42,588.94. If the lower capital investment were obtained, the NPV would reach about £36,816.40 while the higher capital investment induces a longer period to achieve a positive NPV of £28,663.53 (i.e. a longer payback period).

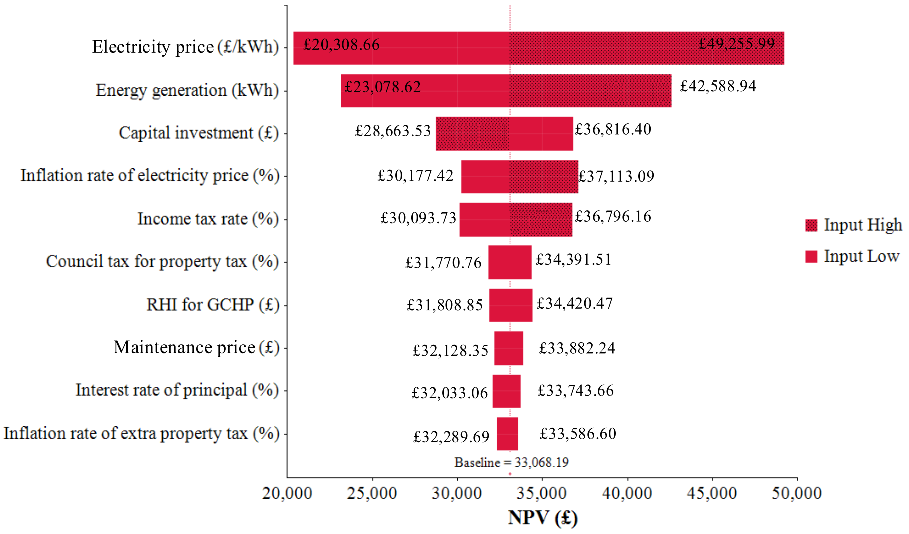
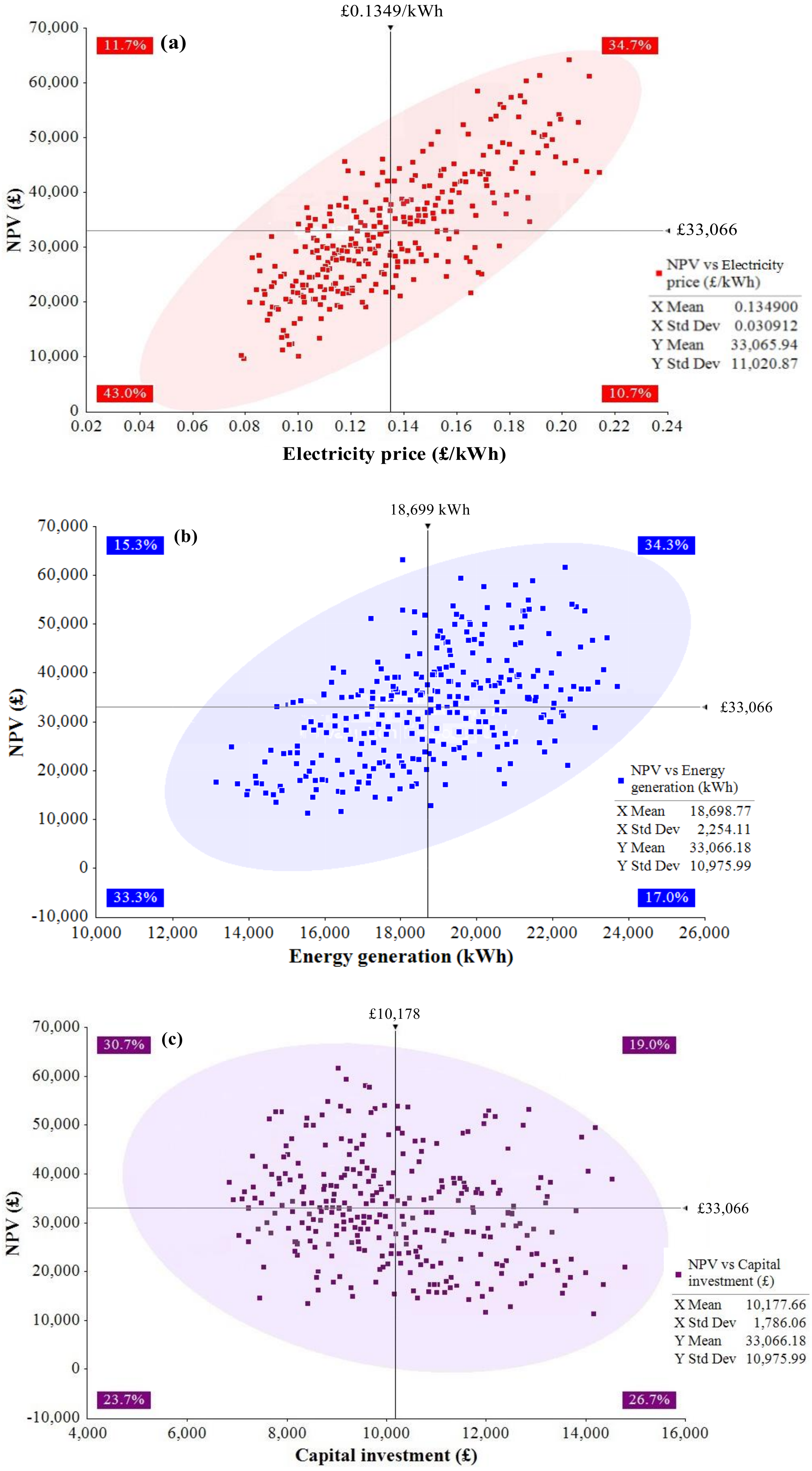


Fig.14. Tornado chart of NPV variation with uncertain input parameters

The NPV variations against electricity price, energy generation, capital cost and discount rate are presented in Fig.15. The horizontal and vertical lines (respective mean values) split the graph into four quadrants with the change of electricity price from £0.06/kWh to £0.22/kWh as shown in Fig.15 (a). The NPV varies from £10,000 to £33,066 accounting for the largest proportion of 43.0% when the electricity price increases from £0.08/kWh to £0.1349/kWh, meanwhile, the smallest proportion of 10.7% occurs when the electricity price further increases from £0.1349/kWh to £0.22/kWh. Likewise, the energy output range of 13,000 kWh to 24,000 kWh affects the savings, cash flows and NPV as presented in Fig.14 (b): the higher energy generation, the greater system performance and larger energy savings, as well as the more NPV and cash flow. When energy output varies from 18,699 kWh to 24,000 kWh, the NPV changes from £10,000 to £33,066 and takes up the biggest proportion of 34.3%, while the NPV lies in the range of £10,000 to £33,066 making up the smallest ratio of 17.0% when the energy output is in the range of 13,000 kWh to 18,699 kWh.



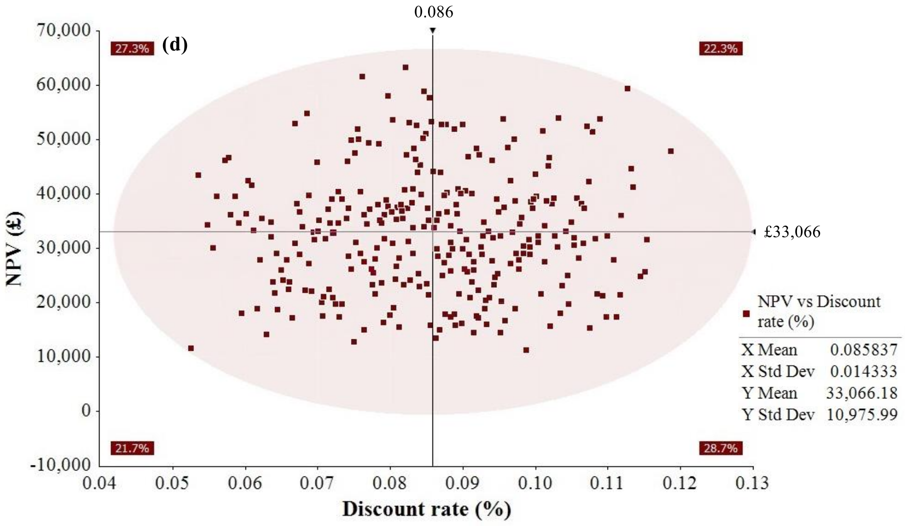


Fig.15. NPV against variations of (a) electricity price; (b) energy generation; (c) capital cost; (d) discount rate

In addition, considering the GCHP system price change in the future, the NPV variation is relative to the capital expense as shown in Fig.15 (c). Compared to the impact of electricity price and energy output, the influence of capital cost is more evenly distributed in the NPV quadrants. For instance, when increasing the GCHP system capital cost from £6,000 to £10,178 and from £10,178 to £15,000, about 23.7% and 26.7% of the NPVs fall below the average value of £33,066, respectively. This demonstrates that the initial cost of the GCHP system is significant to the final judgement of investment as the higher GCHP price leads to the higher capital cost and loan payment. Therefore, the capital price of the GCHP system should be regulated as low as possible for the better market potential. Finally, similar with the capital cost, altering the discount rate also results in an even distribution of the NPV value as given in Fig.15 (d). Higher discount rate weakens the present worth of cash flow and energy output, and decreases the NPV. The lower discount rate is beneficial to the investment of the GCHP system.

4.3.2 Payback period variation with the uncertain input parameters

The payback period is sensitive to several key parameters, including electricity price (£/kWh), capital investment (£) and energy generation (kWh) (see Figs.16-18). Uncertainty associated with electricity price significantly affects the total operating cost (i.e., electricity consumption), energy output and NPV. According to Fig.16, the low electricity price reduces the operating and electricity costs, and increases the payback period up to about 6.18 years relative to the baseline of about 4.31 years. On the other hand, the high electricity price makes the payback period as short as 2.88 years. Likewise, uncertainty in energy output is closely related to the financial credit achieved from reduced electricity consumption. Thus, the range of energy output by using the GCHP system gives rise to a payback period range of approximately 3.51-5.46 years. If lower capital investment can be obtained, the payback period can be achieved about 3.17 years while higher capital investment induces a longer term to achieve positive NPV (up to about 5.70 years).

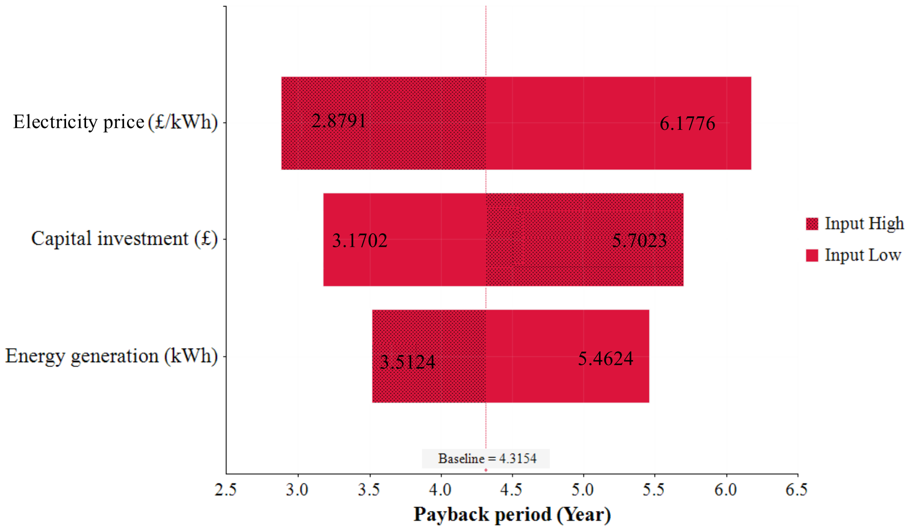
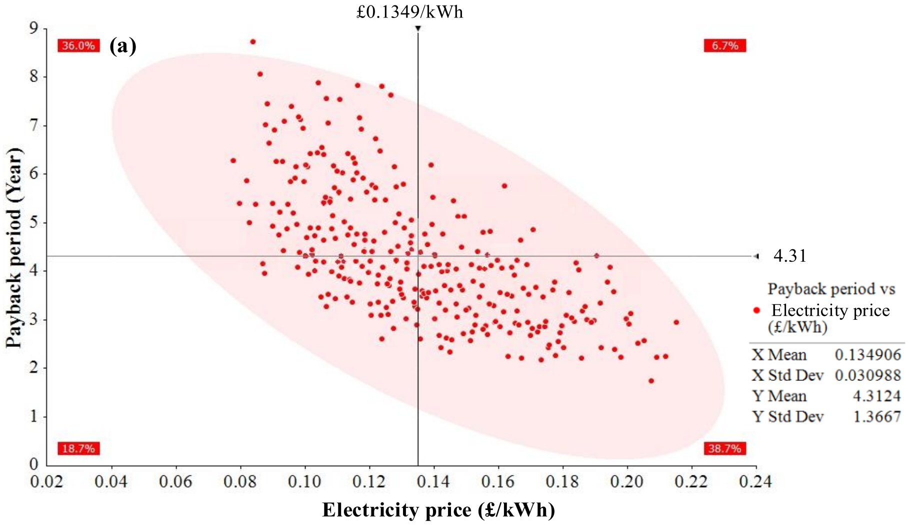


Fig.16. Tornado chart of payback period variation with uncertain input parameters

Fig.17 presents the correlation of payback period. The high electricity price has a good chance (38.7% versus 6.7%) to reduce payback period to below 4.31 years. But for lower electricity price, there is a possibility of 36.0% that payback period is over the mean value as shown in Fig.17 (a). Scenarios in the lower half of Fig.17 (b) have low payback period (<4.31 years) while those in the left-hand side of the figure have lower capital investment (<£10,178). The payback period is therefore located in the lower left quadrant with a possibility of 40.0%. The correlation between the payback period and energy generation presents a pretty even distribution in the four quadrants as shown in Fig.17 (c). The possibility of reducing the payback period below the mean value (4.31 years) is 57.3%, with 20.3% for energy generation lower than 18,699 kWh and 37% for energy generation over 18,699 kWh.



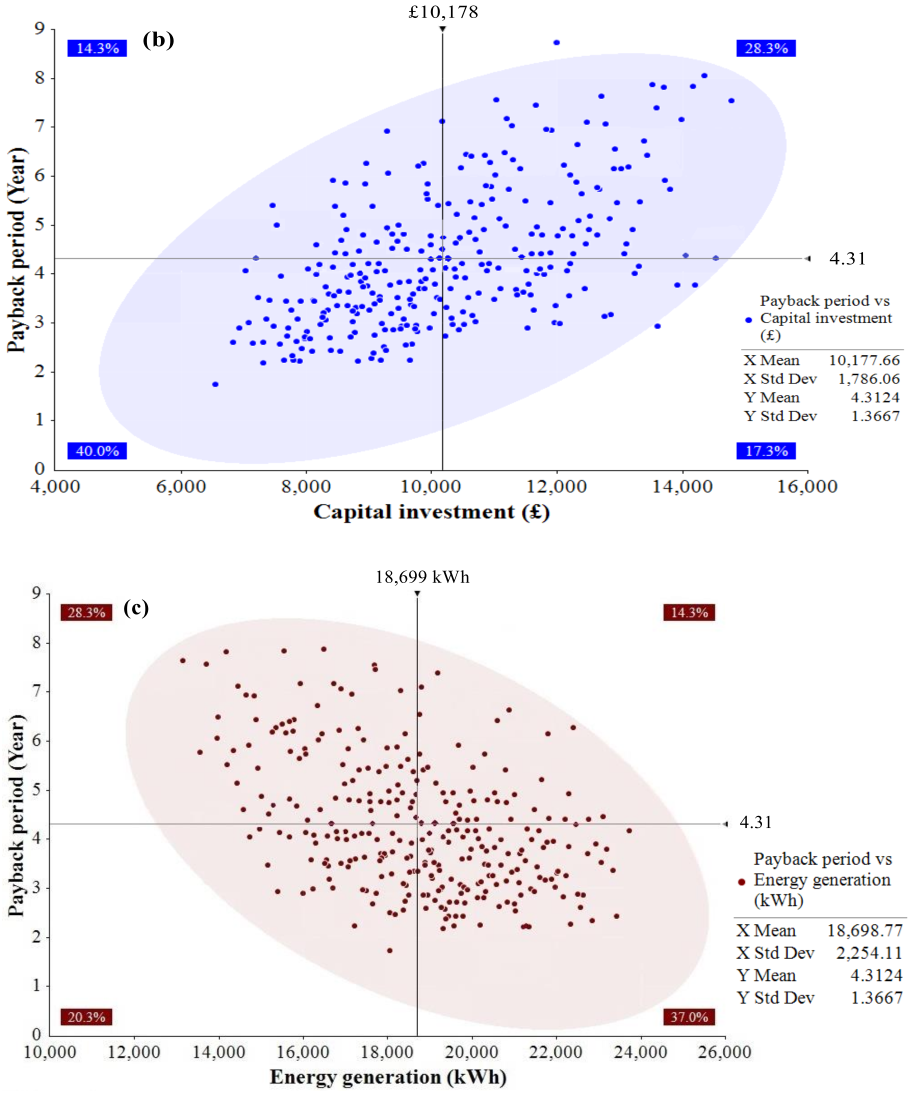


Fig.17. Payback period against variations of: (a) electricity price; (b) capital cost; (c) energy generation

4.3.3 Payback period variation with NPV

It can be seen from Fig.18 that 38.0% of probability NPV value is lower than the average value of £33,066 when the payback period is above the mean value (4.31-8.50 years). Only 4.7% of chance NPV is higher than the average value, indicating the long payback time is detrimental to the total NPV. If payback period can be achieved less than 4.31 years, there is a possibility of 45.0% that the NPV value is higher than the mean value whereas a chance of 12.3% for lower value. This indicates that the high NPV value (the upper left side of the figure) can be achieved when the payback period is shortened in the case.

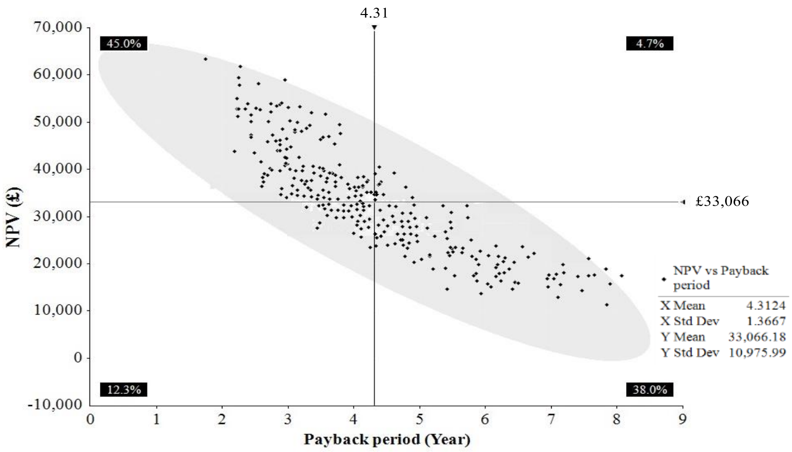


Fig.18. Payback period variation with NPV

5. Conclusions

A techno-economic assessment on a GCHP system with multiple EPs for a domestic building in Birmingham, UK is presented in this paper. 16 EPs are utilized as the ground heat exchangers, and a 5.9 kW nominal heat pump is connected to the EPs. A 2D thermal resistance model of the GCHP system is employed to determine its monthly energy output (heating and cooling), ground energy extracted/rejected, electrical energy consumption and system performance (COP and EER) through the EES software. Furthermore, the financial benefit of the GCHP system is evaluated by using the @Risk software, a complete LCC method with consideration for the time value of money is adopted and some key parameter effects on the LCC are assessed, such as interest rate, income tax rate, LP, SEC, CI, MC, EPT, EPS, ITS, NPV and cumulative EPS. The critical conclusions are obtained as follows:

(1) The energy output (heating and cooling) of the GCHP system could meet the space heating and cooling demands of the domestic building with the annual average COP of 3.63 and EER of 4.62.

(2) The NPV of the GCHP system is £26,095.41 at the market discount rate of 8.75% for a 20-year operating period.

(3) The cumulative EPS becomes positive by the end of the first year, afterwards it keeps positive until the life cycle is completed.

(4) The cumulative SEC saving (£9,166) exceeds the initial cost (£9,033) by the end of the fourth year, the cumulative EPS (£9,531.53) surpasses the remaining principal balance (£7,106.28) by the end of the fifth year. The system payback period is 4.31 years.

(5) The high discount rate reduces the GCHP system energy output and NPV; the low discount rate contributes to the system capital cost.

(6) The payback period is sensitive to electricity price, capital investment and energy output. The high capital investment induces a long term to achieve positive NPV.

For the future research work, a more detailed LCC in comparison with other conventional systems will be investigated.

References

[1] Directive 2010/31/EU of the European parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union; 2010.

[2] Fadejev J, Simson R, Kurnitski J, Haghighat F. A review on energy piles design, sizing and modelling. Energy 2017;122: 390-407.

[3] Habibi M, Hakkaki-Fard A. Evaluation and improvement of the thermal performance of different types of horizontal ground heat exchangers based on techno-economic analysis. Energy Conversion and Management 2018; 171:1177-1192.

[4] Zarrella A, Emmi G, Carli MD. A simulation-based analysis of variable flow pumping in ground source heat pump systems with different types of borehole heat exchangers: A case study. Energy Conversion and Management 2017; 131:135-150.

[5] Emmi G, Zarrella A, Carli MD, Galgaro A. An analysis of solar assisted ground source heat pumps in cold climates. Energy Conversion and Management 2015; 106: 660-675.

[6] Cui Y, Zhu J, Twaha S, Riffat SB. A comprehensive review on 2D and 3D models of vertical ground heat exchangers. Renewable and Sustainable Energy Reviews 2018; 94: 84-114.

[7] You T, Wang B, Wu W, Shi W, Li X. Performance analysis of hybrid ground-coupled heat pump system with multi-functions. Energy Conversion and Management 2015; 92: 47-59.

[8] Rammal D, Mroueh H, Burlon S. Impact of thermal solicitations on the design of energy piles. Renewable and Sustainable Energy Reviews 2018; 92: 111-120.

[9] Zhang W, Cui P, Liu J, Liu X. Study on heat transfer experiments and mathematical models of the energy pile of building. Energy and Buildings 2017; 152: 643–652.

[10] Gultekin A, Aydin M, Sisman A. Thermal performance analysis of multiple borehole heat exchangers. Energy Conversion and Management 2016; 122: 544-551.

[11] Yoon S, Lee SR, Xue J, Zosseder K, Go G H, Park H. Evaluation of the thermal efficiency and a cost analysis of different types of ground heat exchangers in energy piles. Energy Conversion and Management 2015; 105: 393-402.

[12] Saeidi R, Noorollahi Y, Esfahanian V. Numerical simulation of a novel spiral type ground heat exchanger for enhancing heat transfer performance of geothermal heat pump. Energy Conversion and Management 2018; 168: 296-307.

[13] Fadejev J, Simson R, Kurnitski J, Haghighat F. A review on energy piles design, sizing and modelling. Energy 2017; 122: 390-407.

[14] Laloui L, Donna A. Understanding the behaviour of energy geo-structures. Proceedings of ICE, Civil Engineering 2011; 164: 184-191.

[15] Pahud D, Hubbach M. Measured thermal performances of the energy pile system of the dock midfield at Zürich airport. Available at: <https://pangea.stanford.edu/ERE/pdf/IGAstandard/EGC/2007/195.pdf > 2007 [Assess 06.2007].

[16] Fisch MN, Himmler R. International solar centre Berlin – a comprehensive energy design. In: Fifth international conference for enhanced building operations. Pittsburgh, Pennsylvania, USA, 2005.

[17] Brandl H. Thermo-active ground-source structures for heating and cooling. Procedia Engineering 2013; 57: 9-18.

[18] Suckling TP, Smith PEH. Environmentally friendly geothermal piles at Keble College, Oxford, UK. International conference on piling and deep foundations 2002; 445-452.

[19] Laloui L, Donna AD. Energy geostructures: innovation in underground engineering. Wiley-Blackwell 2013.

[20] Ozudogrua TY, Olgunb CG, Senola A. 3D numerical modelling of vertical geothermal heat exchangers. Geothermics 2014; 51: 312–324.

[21] Hamada Y, Saitoh H, Nakamura M, Kubota H, Ochifuji K. Field performance of an energy pile system for space heating. Energy and Buildings 2007; 39: 517–524.

[22] Darkwa J, Su W, Chow DHC. Heat dissipation effect on a borehole heat exchanger coupled with a heat pump. Applied Thermal Engineering 2013; 60: 234–241.

[23] Kim J, Jang JC, Kang EC, Chang KC, Lee EJ, Kim Y. Verification study of a GSHP system manufacturer data based modelling. Renewable Energy 2013; 54:55–62.

[24] Capozza A, Zarrella A, Carli MD. Long-term analysis of two GSHP systems using validated numerical models and proposals to optimize the operating parameters. Energy and Buildings 2015; 93: 50–64.

[25] Bristow D, Kennedy CA. Potential of building-scale alternative energy to alleviate risk from the future price of energy. Energy Policy 2010; 38 (4): 1885–1894.

[26] Yoon S, Lee SR. Life cycle cost analysis and smart operation mode of ground source heat pump system. Smart Structures and System 2015; 16 (4): 743–758.

[27] Chiasson AD. Life-cycle cost study of a geothermal heat pump system bia office building, Winnebago, NE. Midwest Research Institute (Geo-Heat Center, Oregon Institute of Technology), 2006.

[28] Morrone B, Coppola G, Raucci V. Energy and economic savings using geothermal heat pumps in different climates. Energy Conversion and Management 2014; 88: 189-198.

[29] Vu NB, Lee SR, Park S, Yoon S, Go GH, Kang HB. Life cycle cost analysis for ground-coupled heat pump systems including several types of heat exchangers. International Journal of Architecture, Engineering and Construction 2013; 2: 17-24.

[30] Ren C, Deng Y, Cao SJ. Evaluation of polyethylene and steel heat exchangers of ground source heat pump systems based on seasonal performance comparison and life cycle assessment. Energy and Buildings 2018: 162: 54-64.

[31] Canbek C. Life-cycle cost study of ground source heat pumps in hot humid climate zone. Florida International University. Available at: < http://digitalcommons.fiu.edu/cgi/viewcontent.cgi?article=3200&context=etd> 2010 [Accessed 10.2010].

[32] Zhu Y, Tao Y, Rayegan R. A comparison of deterministic and probabilistic life cycle cost analyses of ground source heat pump (GSHP) applications in hot and humid climate. Energy and Buildings 2012; 55: 312-321.

[33] Lu Q, Narsilio GA, Aditya GR, Johnston IW. Economic analysis of vertical ground source heat pump systems in Melbourne. Energy 2017; 125:107-117.

[34] Arat H, Arslan O. Exergoeconomic analysis of district heating system boosted by the geothermal heat pump. Energy 2017; 109:1159-1170.

[35] Saner D, Juraske R, Kubert M, Blum P, Hellweg S, Bayer P. Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems. Renewable & Sustainable Energy Review 2010; 14 (7): 1798–1813.

[36] Huang B, Mauerhofer V. Life cycle sustainability assessment of ground source heat pump in Shanghai, China. Journal of Cleaner Production 2016; 119: 207–214.

[37] Hong T, Kim J, Chae M, Park J, Jeong J, Lee M. Sensitivity analysis on the impact factors of the GSHP system considering energy generation and environmental impact using LCA. Sustainability 2016; 8 (4): 376-388.

[38] Gabrielli L, Bottarelli M. Financial and economic analysis for ground-coupled heat pumps using shallow ground heat exchangers. Sustainable Cities and Society 2016; 20: 71-80.

[39] Wood CJ. Investigation of novel ground source heat pump, in: Built Environment, Vol. Doctor of Philosophy, University of Nottingham, 2009.

[40] Wood CJ, Liu H, Riffat SB. An investigation of the heat pump performance and ground temperature of a piled foundation heat exchanger system for a residential building. Energy 2010; 35: 4932-4940.

[41] Greenline HT Plus. Available at: <http://www.intelligentenergysolutions.com/assets/images/Datasheets/Ground Source Heat Pumps/IE SIVT Green line HTPlus.pdf > 2008 [Accessed 09.2008].

[42] Girard A, Gago EJ, Muneer T, Caceres G. Higher ground source heat pump COP in a residential building through the use of solar thermal collectors. Renewable Energy 2015; 80: 26-39.

[43] Arat H, Arslan O. Exergoeconomic analysis of district heating system boosted by the geothermal heat pump. Energy 2017; 109:1159-1170.

[44] Sharqawy M, Mokheimer EM, Badr HM. Effective pipe-to-borehole thermal resistance for vertical ground heat exchangers. Geothermics 2009; 38: 271–277.

[45] Loveridge F, Powrie W. 2D thermal resistance of pile heat exchangers. Geothermics 2014; 50: 122-135.

[46] Cui Y, Zhu J. Year-round performance assessment of a ground source heat pump with multiple energy piles. Energy and Buildings 2018; 158: 509-524.

[47] Zanchini E, Jahanbin A. Effects of the temperature distribution on the thermal resistance of double u-tube borehole heat exchangers. Geothermics 2018; 71: 46-54.

[48] Kambanou ML, Lindahl M. A literature review of life cycle costing in the product-service system context. Procedia CIRP 2016; 47:186-191.

[49] Chong WT, Naghavi MS, Poh SC, Mahlia TMI, Pan KC. Techno-economic analysis of a wind–solar hybrid renewable energy system with rainwater collection feature for urban high-rise application. Applied Energy 2011; 88: 4067–4077.

[50] Buker MS, Mempouo B, Riffat SB. Performance evaluation and techno-economic analysis of a novel building integrated PV/T roof collector: An experimental validation. Energy and Buildings 2014; 76: 164-175.

[51] Energy price – Parliament UK. House of Commons Library. Available at: <https://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN04153 > 2018 [Accessed 02.2018].

[52] Ofgem. Domestic renewable heat incentive. <https://www.ofgem.gov.uk/environmental-programmes/domest ic-rhi>.

Nomenclature

A	Surface area of the U-tube pipe (m^2)
C	Cost (£)
D_H	Hydraulic dimeter (m)
d	Discount rate (%)
E	Energy generation (kWh)
G	Principal payment (£)
h	Heat transfer coefficient [$W/(m^2 \cdot K)$]
k	Period of maintenance payments
L	Energy pile length (m)

N	Period of economic assessment
Nu	Nusselt number
n	Polytropic compression coefficient
P	Pressure (kPa)
Pr	Prandtl number
R	Thermal resistance (K/W)
Re	Reynolds number
r	Radius (m)
s	Year number of periodic payments
T	Temperature (°C)
t	Time (s)
U	Overall heat transfer coefficient ($W/m^2\cdot K$)
W	Rate of work input (kW)
z	Number of loan payment years

Subscripts

c	Cooling output from heat pump
comp	Compressor
fluid	Fluid
h	Heat output from heat pump
inlet	Inlet fluid temperature
outlet	Outlet fluid temperature
pipe	Pipe
pump	Pump

soil	Soil
total	Total

Greek Letters

α	Period of extra property tax (%)
β	UK electricity rate (£/kWh)
γ	Inflation rate of extra property tax (%)
ζ	Number of pipes in the EP
λ	Thermal conductivity ($W/m^2 \cdot K$)
ρ	Density (kg/m^3)
υ	Working fluid velocity (m^2/s)
μ	Working fluid dynamic viscosity ($Pa \cdot s$)

Abbreviations

ASHP	Air source heat pump
CI	Capital investment
COP	Coefficient of performance
DC	Direct expansion
DCFA	Discounted cash flow analysis
DPB	Discounted payback time
EER	Energy efficiency ratio
EES	Engineering equation solver
EP	Energy pile
EPS	Energy pile system savings
EPT	Extra property tax

ETR	Effective tax rate
GHE	Ground heat exchanger
GCHP	Ground-coupled heat pump
ITS	Income tax savings
LCA	Life-cycle assessment
LCC	Life-cycle cost
LMTD	Logarithmic mean temperature difference
LP	Loan payment
MC	Maintenance cost
NPV	Net present value
PC	Periodic cost
RHI	Renewable heat incentive
SEC	System energy cost
SPB	Simple payback period