Assess the benefits of ground- source-heat pumps for residential heating versus natural gas boilers in the UK

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Abstract. Some basic introduction about the current background of heating in the UK and ground source heat pumps (GSHPs) and natural gas (NG) boilers was outlined in this report. Moreover, this report also provided a detailed literature-based review of previous studies of both GSHP and NG boiler, concentrating on environmental impact, costs and benefits. For the purpose, a 12kW peak heating load house which is located in London established by the IES VE have been considered as the case study. Finally, it is concluded that the coefficient of performance (COP) of GSHP should be higher than 2.2 to achieve lower carbon emissions compared with NG boilers in the current period. And under normal conditions, the efficiency of the GSHP is in the range of 2.2 to 4, so it is more environmentally friendly than the NG boiler. As for a GSHP with a COP of 4, it has been found that the carbon emissions will be reduced by about 25% in the current period, 40% in 2030 and even 90 percent in 2050 after replacing the NG boiler. Besides, the results show that using low operating temperatures will contribute to reduce carbon emissions. In the aspect of economic, it can be concluded that the installation of the GSHP is cost-effective in most cases and the higher the COP, the shorter the payback period. Under the subsidy of Renewable Heat Incentive (RHI), for a GSHP with a COP of 4, its payback period is about 20 years. However, if the COP is lower than 2.6, the capital costs cannot be fully recouped. In the end, the results and the limitations occurring in the research process have been analysed and advice on future improvements was given.

Keywords: GSHP, nature gas boiler, carbon emission, model-based simulation, life cycle assessment.

1. Introduction

1.1. Background

The heat sector accounts for almost half of all energy consumption in the UK, most of which is used for space heating, hot water and cooling in buildings [1]. At present, most of the heating demand is met by the combustion of natural gas. Natural gas, as a kind of fossil fuel, a lot of carbon is emitted during combustion, resulting in some environmental pollution [2]. According to the government's carbon program [3], the plan sets the scale of the challenges associated with achieving the UK's 2050 carbon reduction target, and by 2050, building emissions will need to be reduced to near zero, which means the heating sector is almost completely decarbonized. In response to this challenge, some other renewable energy has been considered to instead of fossil fuel.

As electricity generation is rapidly decarbonized in the UK, heat pumps are expected to be one of the main low or zero carbon technologies for heating and cooling of buildings. Basically, there are three kinds of heat pumps, respectively are air-source heat pump, ground-source heat pump and water-source heat pump. At present, GSHP systems are the most used in the world because of the high efficiency and stable performance compared with other two kinds of heat pumps. As an energy source, geothermal heat is local, reliable, resilient, environmentally-friendly, and sustainable. This natural energy is produced from the heat within the earth and the sun radiation, which has different applications, such as heating and cooling of buildings, generating electricity [4]. Heat pump technology can offer a promising opportunity to help achieve deep decarbonization of the building sector.

However, the application of GSHPs is at the demonstration stage in the UK [5]. Therefore, many feasibility studies are still needed for GSHPs. Geological features, including ground temperature, hydrological conditions, and thermal characteristics of the GSHP exchanger locations, are decisive factors in the relative cost and design of the system[4]. Basically, there are four main types of GSHPs, such as ground water heat pumps (GWHP), ground-coupled heat pump (GCHP), surface water heat pump (SWHP) and a standing column well (SCW). The opportunity to implement a HP in a heating system results on the basis of energy indicators and economic analysis. Some factors will affect the cost and GHG emission.

GSHP can be installed almost anywhere [6], but system type, open loop or closed loop; the selection of ground collector loop, horizontal or vertical, and the size of the loop all depend on local geological conditions [7]. So far, most of Britain's installations are for heating (with the exception of the recent demand for cooling in London). It is essential that the design of the wells for an open loop system or the collector loop for a closed loop system is optimized to meet the heating or cooling demand of the building.

GSHPs can be used to provide space and domestic water heating for buildings of all types and sizes, and for space cooling if needed. For example, GSHPs can be used for cooling in the future when indoor overheating occurs due to increased global warming although providing cooling in addition to heating will result in an increase in energy consumption. GSHPs are particularly suitable for new buildings because they are most effective when for proving low temperature distribution systems such as underfloor heating. They can also be used for retrofitting, especially in conjunction with measures to reduce heat demand.

As mentioned in some studies, the main method that can be used in order to assess the environmental impacts of a GSHP system over its whole lifecycle is Life Cycle Assessment (LCA) because it can provide more comprehensive and reasonable analysis on the energy and environment impact of product for the whole life cycle [8]. Moreover, there are many economic analysis methods used to evaluate the economic performance of heating systems. These include the life cycle cost method, net benefits (net present worth) method, payback method, benefit-to-cost (or savings-to-investment) ratio method, internal rate-of-return method, overall rate-of-return method, exergy and cost energy mas method, and the analytical hierarchy process [9].

1.2. Review of Economic and Environmental Assessment Conclusions

This section describes how GSHPs can be best applied to deliver the savings in CO_2 emissions and reduce cost resulting from the use of GSHPs in comparison to natural gas boilers. Moreover, the relationship between the COP of GSHPs and carbon emissions concluded in previous studies was mentioned as well.

According to previous study [10], it was suggested that a heat pump must achieve a system efficiency greater than 2.6 in order to reduce carbon emissions compared with a new high-efficiency gas-fired boiler, because the carbon emission factor of electricity in the UK is high. If the system efficiency reaches 3.0, the emissions can be reduced by 13%, which directly shows the benefits of heat pump in reducing greenhouse gases.

The greenhouse gas emission reduction of the installed GSHP systems for space heating in Europe was comprehensively studied [11]. They estimated that GSHP systems save 3.8 million tons of greenhouse gas emissions (0.74% of the total) from residential heating in 19 European countries compared with traditional technologies. They also estimate that if all fossil fuel, power and wood-fired boilers are replaced by GSHP with SPF of 3.5, an average of up to 30% of carbon dioxide emissions can be saved in space heating. With the increase of GSHP's higher performance factors and RES share in power generation, the carbon content is getting lower and lower, and the impact may increase in the future.

GSHP Association provided an indication of the range of costs for GSHP systems, shown in Table 1, using different types of ground heat exchangers [12]. It is assumed that all the systems are ground to water.

Table 1. Indicative capital costs for individual ground-to-water heat pump systems

System type	Ground coil costs (£ /kW)	Heat pump costs (£/kW)	Total system costs (£/kW)
Horizontal	250-400	350-750	600-1150
Vertical	550-750	300-750	850-1500
*Costs include installation and commission of the heat pump and ground loop			

What's more, another organization, the centre for renewable energy sources and saving in Europe shows the installation costs of different kinds of GSHPs and are listed in Figure 1. Besides, it is also mentioned that the maintenance cost of GSHP systems is low compared to most alternative options because most of the components have a long lifespan even 15 years [13].

	Open system	Closed horizontal system	Closed vertical system
Borehole / heat exchanger	50–60 €/m (drilling) Performance depending on ground	8–12 €/m^2 (one layer at 30 cm) Performance 18–25 W/m	40–50 €/m (heat exchanger) Performance depending on ground
Heat pump	Small systems (0–50 kW): 300–400 €/ kW Large systems (> 50 kW): < 300 €/ kW		
Heating / cooling distribution	Fan-coils: 150–200 €/kW Underfloor: 60–80 €/kW In-wall: around 60–80 €/kW		
Engineering cost (materials & labor)	For 10 kW: 1500 €		
For heating: COP=5–6 / SPF_{th}=4.5–5.5 – For cooling EER=4.5–5.5 / SPF_c=4–5			

Figure 1. Installation costs of GSHPs

Besides, Local Government Association issued a report indicating the payback period, shown in Table2, required to replace three kinds of mainstream traditional heating systems by using GSHPs [14].

Table 2. Renewable Heat Incentive (RHI) Payback on GSHP Installations

Traditional Fuel Replaced	Payback period with RHI	Payback period without RHI	Estimated Annual payments
Direct Electric Heating	6-8 years	12-18 years	£2,610-3,940
New Oil Boilers	12 years	29 years	£2,610-3,940
New Gas Boilers	14 years	47 years	£2,610-3,940

In terms of economic evaluation of GHSP, Nagano et al. [15] took Sapporo, Japan as an example and found that the payback period of increased investment cost of GSHP system is 10 years compared with that of oil-fired boiler and air conditioning system, 9 years compared with that of gas-fired boiler and air conditioning system, and 14 years compared with that of air conditioning heat pump system.

1.3. The factors of influencing the performance of GSHPs

The configuration of ground source heat pump (GSHP) systems can vary according to numerous parameters. Many of these parameters affect the physical requirements of the product itself, and as such will impact the upfront cost. Other parameters, including the operating conditions, may not have a significant impact on cost, but will affect the efficiency of the heat pump and will therefore impact the different performance parameters: namely the share of the demand met by the heat pump, the CO2 emissions savings compared to a boiler, and the peak electricity demand [16]. And the various parameters that distinguish HHP systems addressed in this analysis is shown in Table 3.

Table 3. Factors influencing the performance of GSHPs

Factors	Examples & Explains
Type of heat pump	Open loop, vertical closed loop, Horizontal closed loop
Heat pump size	Depend on the heat demand
Operation temperature	Low temperature (35 ℃) or medium temperature (55℃)
Ground temperature	Affected by seasons

The design and performance of the ground element of HPs depend on key parameters such as initial ground temperature, thermal conductivity and specific heat capacity. However, the cost of obtaining site-specific thermal parameters may account for a large proportion of the total capital costs of the installation. Kim et al. [17] studied the performance of GSHP system installed in a Korean school Kim building. In their experiments, they monitored ground temperatures at different depths. The results show that the ground temperature is not affected by the outside ambient temperature after 10 meters deep and in a COP of heat pump in heating mode varied from 4.3 to 8.3.

1.4. Aim and Objectives

The aim of this research is to assess the economic costs and environmental impact in the UK of a fuel switching strategy focused on the replacement of natural gas boilers by ground-source heat pumps supplied by electricity with a fast-decreasing carbon content. What's more, the objectives include:

- Establish simulation model using IES VE software
- Environmental impact analysis in GSHPs and natural gas boilers
- Economic cost analysis in GSHPs and natural gas boilers
- Compare the benefits and shortage of GSHP systems and natural gas boilers
- Assess the challenges

2. Methodology

This section outlines the methods which were used throughout the various stages of this research project. Basically, quantitative data collection and analysis were used while studying the economic costs, environmental impact and benefits between GSHPs and natural gas boilers used for residential heating in the UK. Because quantitative method contributes to make this research is based firmly in numbers and clear, concrete, measurable facts, which is easy to compare and more persuasive.

2.1. Summary of approach taken

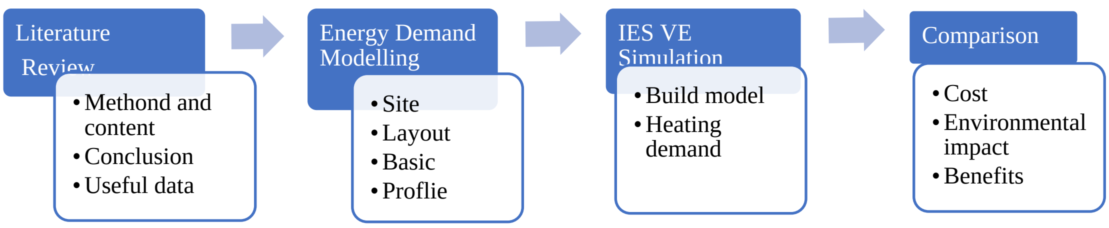
The first stage is to conduct a literature review to ensure that no same investigations had been conducted and to understand the various elements involved in the project. The project involved assessing the economic and environment costs and benefits between GSHPs and NG boilers therefore it is necessary to gain an understanding of the difference between the two technologies in carbon emission and overall cost, particularly regarding the coefficient of performance, carbon emission factor and energy price.

To meet the aim of this research, the basic methodology involved establishing a model house that represented a range of typical heating demand, and modelling the house using IES VE software. Then based on the house, various types of GSHPs and NG boilers can be simulated for heating in this house. Originally, the COP values of GSHPs and NG boilers were taken from actual performance in the field study, rather than manufacturer's test data so that the study was more practical. The performance parameters of the heating systems that designed for the model house and the carbon emission factor could be modified in the IES VE based on the set values.

While the energy modelling was designed to systematically compare the economic and environmental costs between GSHPs and NG boilers, the next part was to run the simulation by using IES VE software to obtain the annual heating demand and the carbon emissions of heating systems. The values of annual heat demand were typically used to size the heating capacity of the equipment. And it is important that for the model house, the peak heating load could be met by both GSHPs and NG boilers within the range of those had been designed. After performing a simulation, change the heating systems and modify the parameters (COP or carbon emission factor) and repeat the previous steps.

To that end, the comparison was divided into two parts. First, comparison of two heating technologies at the current stage was made, and then the future prediction was made. The carbon emissions of both GSHPs and NG boilers can be obtained from the IES VE data report. And the running cost of them can be calculated by using equation. In this research, the effects of various factors on carbon emission can be more comprehensive and clearer by adopting a variable control approach. And the capital costs of GSHPs and NG boilers were calculated based on the product costs, installation and emitter replacement costs and maintenance costs to compare. The lifetime cost and carbon emissions comparison are based on the cost and performance data gathered, modelled and analyzed through the IES VE software. The flow path of this research is shown in Table 4. And the detailed description about each step was shown in the following sections.

Table 4. Flow path



2.2. Energy Demand Modelling Establishment

In this research, the overall aim of the energy modelling was to systematically compare the performance of GSHPs to NG boilers for residential heating in different conditions. By using energy modelling and standardizing the model house, multiple simulations by changing a single variable can help to make the study more detailed.

2.2.1 The Geometry of Model House

The tendered building is located at the city centre in London and used as private house with an orientation facing south-east. It has two stories including three bedrooms, one kitchen, one dining room and two toilets. The appearance of the house is shown in Figure 2.

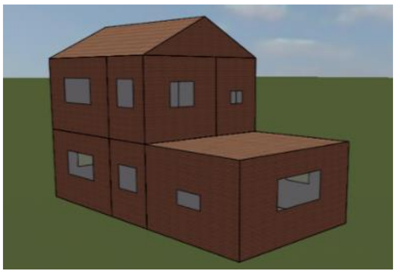


Figure 2. Model house

The detailed fabric parameters are shown in Table 5

Table 5. House parameters

Item	Small house (75 m^2)
Surace area (m^2)	206
Glazing area(m^2)	30.9
Glazing ratio	0.15

2.2.2 Key specifications

As mentioned in the literature review, renewable technologies were not recommended to install in the house with low thermal performance, so the research direction mainly focuses on the well-insulated houses. Table 6 shows the key specifications of the model house. Basically, the thermal properties of building structures are based on the 2013 UK Building Regulations and the internal built environment design are according to the CIBSE GUIDE A.

Table 6. Key specifications

Item	Specifications of original building
Occupancy	Four person at 125 W/person
Equipment	10 W/m^2
Lighting	12 W/m^2
Infiltration	1 ach
Ventilation rate	10L/person/s
Heating set point	23℃ during occupied hours and 18 ℃ at other times
Time of heating off	No
External wall	150mm dense concrete (with insulation) U-value is 0.26 W/m^2K
Roof	100mm concrete desk (with insulation) U-value is 0.18 W/m^2K
Window	12mm double plane glazing. U-value is 1.6 W/m^2K
Ground floor	300 mm dense concrete on 750 mm London clay (with insulation) U-value is 0.22 W/m^2K
Internal partitions	12.5 mm plasterboard, 50mm air cavity, 12.5mm plasterboard U-value is 1.788 W/m^2K
Heat recovery	No

2.3. Heating Systems Modelling Cases

To develop the model house with GSHPs and NG boilers, the model house's shape and enclosure characteristics were unchanged but the heating systems will be changed. In this research project, three different efficiency levels of GSHP systems and one mainstream NG boiler were applied. Besides, it was assumed that the model house has no air conditioning system because only GSHP applications in heating were studied in this research although GSHP systems can be used for cooling as well. The GSHP and NG boiler cases are shown below.

2.3.1 GSHPs and NG boilers

Two types of GSHPs, vertical closed loop and horizontal closed loop were chosen as the cases because they are more suitable for residences. The range of COPs for these GSHPs was provided by the Energy Saving Trust's heat pump field trip, rather than relying on estimates or manufacturer's COP data at test conditions in order to be more realistic. As for the NG boilers, the products widely used in the market are similar, so only one type NG boiler was selected. Besides, the COP of GSHPs were influenced by the product performance, climate and design conditions. Therefore, after considering these impacts comprehensively, three different levels of system COP values, shown in Table 7, were assumed using the energy modelling to study the impact of COP and heating method on carbon emissions.

Table7. Heating systems COPs:

Item	Heating COP	
	Low-temperature operation 35°C	Medium-temperature operation 55°C
Low COP GSHPs	3.3	2.2
Medium COP GSHPs	3.8	2.6
High COP GSHPs	4.4	3.2
NG boilers	0.85	

2.3.2 Assuming the Future Carbon Emission Factor of Electricity and Natural Gas

As mentioned in the literature review, it can be considered that the carbon emission of GSHP is due to the process of producing electricity. Basically, the future carbon emission factor should be predicted based on future plan provided by the UK's future carbon reduction target. In the future, the grid electricity carbon intensity is assumed to fall to 0.117 kg CO_2/kWh by 2030 and 0.028 kg CO2/kWh by 2050. Moreover, over the next 30 years, the predicted carbon emission factor of electricity is shown in Figure 3. However, the emission factor of natural gas was assumed to remain constant to 2050, as the proportion of methane (CH_4) in natural gas is relatively unchanging. The detailed values were shown in Table 8.

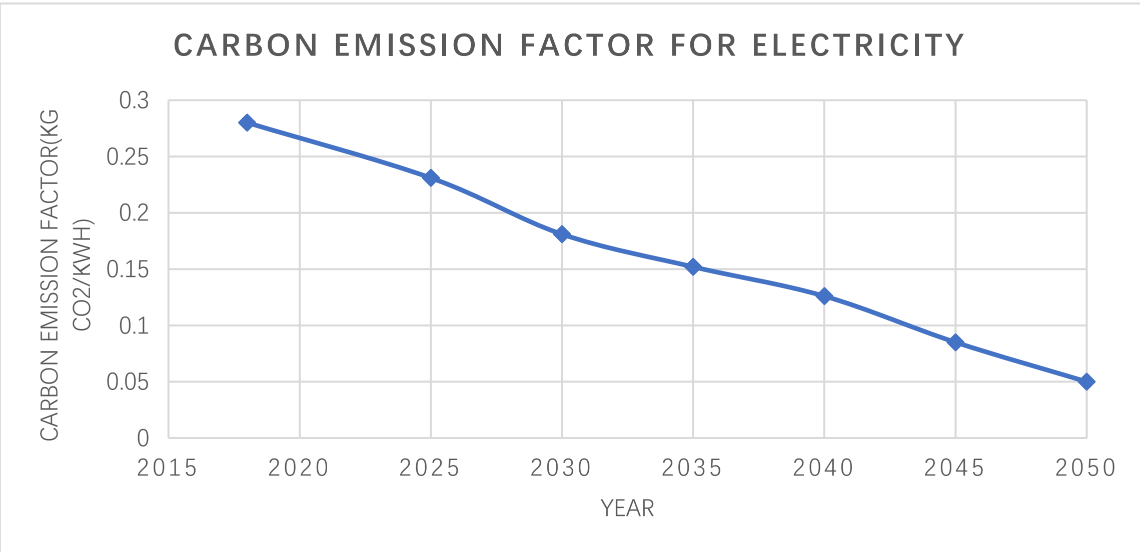


Figure 3. Predicted carbon emissions of electricity from 2018 to 2050

Table 8. Carbon emission factor

Carbon emission factor	2018	2030	2050
Electrical	0.28088	0.18	0.05
Natural gas	0.216	0.216	0.216

2.3.3 Assuming the Future Prices of Electricity and Natural Gas

In the UK, because the prices of electricity at night and during the day are different, they need to be considered separately. Besides, the price of electricity depends mainly on the type of fuel, government funding and weather condition, so that taking the average value in different scenarios is better for research. As for the natural gas, its price can be considered relatively stable for some time, but it will gradually rise as the government may impose higher taxes to reduce the use of natural gas in the future. Based on two reports [18], the predicted prices of electricity at night and during the day and natural gas from 2018 to 2050 can be obtained.

2.4. Equation

In order to determine the emission factor of the current UK grid electricity, following equations are used.

$$\text{Equation Factor}\ \left(\frac{\mathrm{CO}_{2-eq}}{\mathrm{kWh}}\right) = \sum \text{Electricity percentage}(\%) \times \text{Emission Factor}\ (\mathrm{g/kWh}) \quad (1)$$

Where the electricity percentage (%) refers to the proportion of different fuels used for power generation.

The carbon emission reduction can be calculated using the equation below.

$$\mathrm{CO}_{2(\mathrm{reduction})} = \mathrm{CO}_{2(Boiler)} - \mathrm{CO}_{2(\mathrm{GSHP})} \quad (2)$$

Where $\mathrm{CO}_{2(\mathrm{boiler})}$ is the carbon emissions of natural gas boiler

$\mathrm{CO}_{2(\mathrm{GSHP})}$ is the carbon emissions of GSHP system

Payback period which indicates the length of the time required to recover the cost of an investment can be obtained from

$$\mathrm{PP} = \frac{C_o}{C_{income}} \quad (3)$$

Where C_0 is the capital costs, and C_{income} is the running cost saving.

3. Results and Discussions

3.1. Energy Demand

3.1.1 Building Heating Load and Cooling Load

The total heating or cooling load of the model house in one year, shown in Figure 4, was obtained from IES VistroPro report. These loads were simulated under the conditions that the indoor temperature was assumed at 23 ℃ during occupied hours and 18 ℃ at other times all the year.

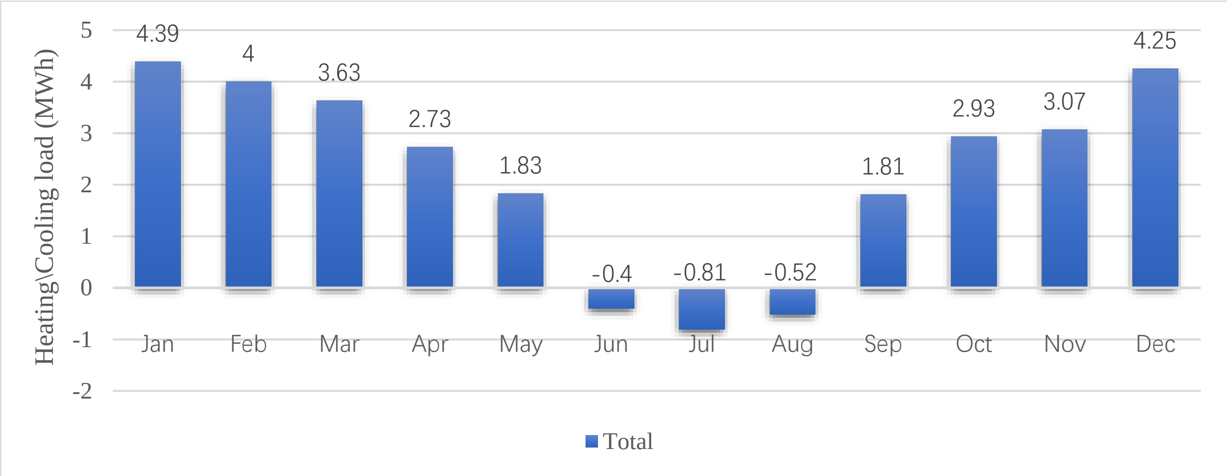


Figure 4. Monthly total heating load and cooling load of the model house

From Figure 4, it was found that air conditioning is needed to provide cooling in June, July and August, when the indoor temperature is higher than the set value. In heating season, lower outdoor temperature, resulting in a relatively large heating load. The heating load in January was the largest, at 4.39 MWh, and the cooling load in July was the largest, at 0.8 MWh. The total cooling load is much lower than the heating load in one year.

3.1.2 Systems Energy Demand

The energy demand for each heating or cooling systems was also obtained from the IES VE VistroPro report based on their specific COP values and is shown in Table 9.

Table 9. Annual Electricity and Gas Demand

Item	**Annual Electricity Demand (MWh)**	
	Floor Heating (35°C)	Radiator(55°C)
GSHP Low COP	11.53	17.3
GSHP Medium COP	10.42	14.79
GSHP High COP	9.13	12.19
	Annual Natual Gas Demand (MWh)	
NG Boiler	38.68	38.68

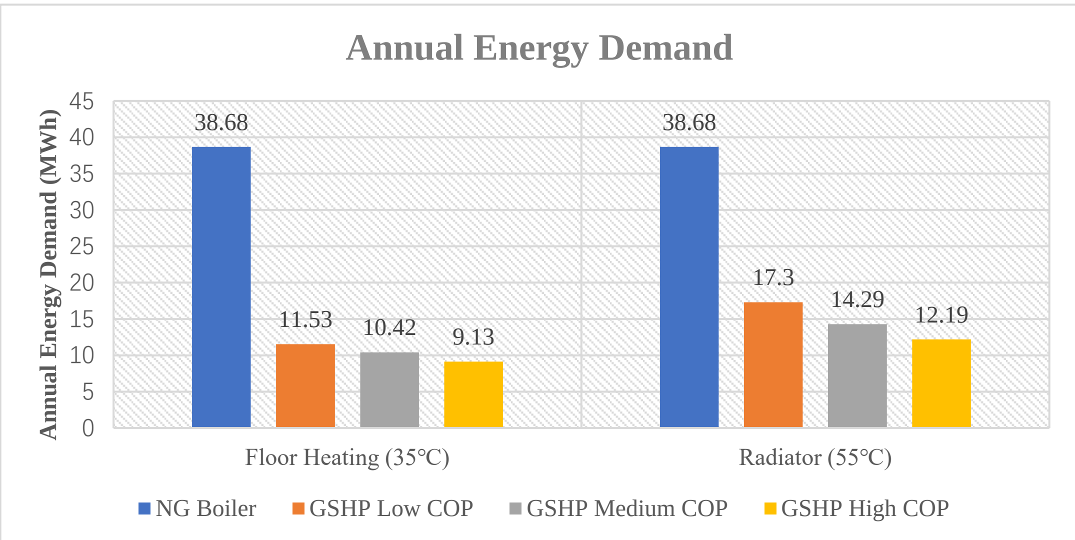


Figure 5. Annual Energy Demand

According to Figure 5, it is clear to see the energy consumption of GSHPs with three different COP values and NG boilers for heating in two heating methods. Besides, NG boilers require about two to four times as much energy as ground-source heat pumps, depending mainly on the efficiency and operating temperature of GSHPs. For a constant heating load, the ground source heat pump with 400% efficiency consumes the least energy when the operating temperature is 35 degrees.

3.2. Comparison in Carbon Emissions

According to the IES VE simulation results, the current and future prediction about the annual carbon emissions of each systems for heating the model house is shown in Table 10. And the data is made to a bar chart, which is shown in Figure 6.

Table 10. Annual carbon emissions for GSHPs and NG boiler

Year	Cases	Carbon emissions (kg CO_2/year)	
		Floor Heating (LWC 35 ℃)	Radiator (LWC 55 ℃)
2018	GSHP low COP	6152	8978
	GSHP Medium COP	5408	7673
	GSHP High COP	4739	6329
	NG boilers	n/a	8649
2030	GSHP low COP	2076	3134
	GSHP Medium COP	1876	2661
	GSHP High COP	1644	2195
	NG boilers	n/a	8649
2050	GSHP low COP	577	865
	GSHP Medium COP	521	739
	GSHP High COP	457	610
	NG boilers	n/a	8649

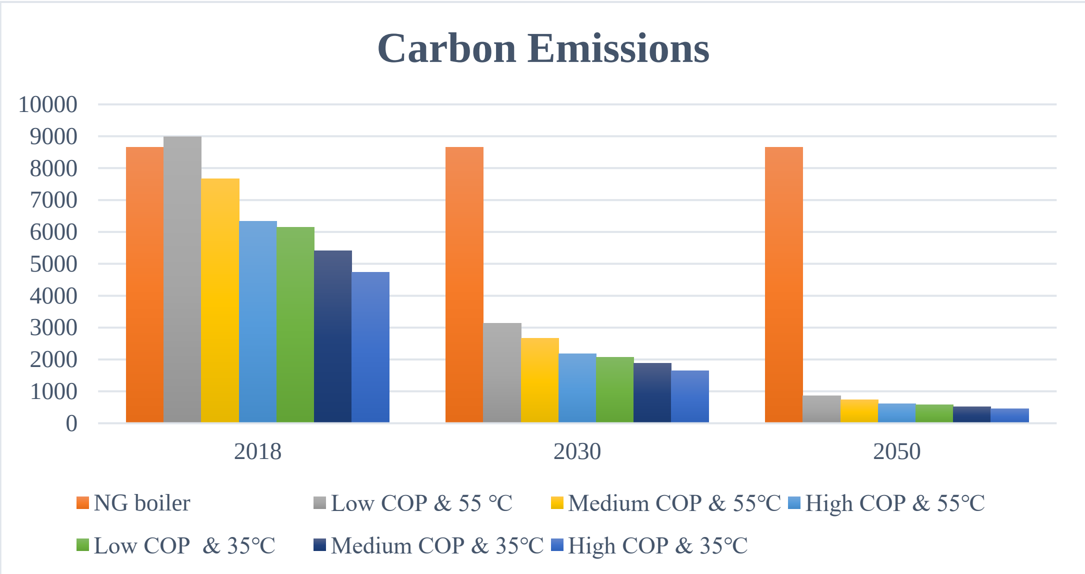


Figure 6. Carbon emissions from six GSHP cases and NG boiler in 2018,2030 and 2050

From the above table and figure, the carbon emissions of GSHP systems in six conditions and a NG boiler system that were used to provide heating for the model house in different periods can be compared clearly. It can be seen that the annual carbon emissions of 2018 generated by low COP GSHPs heating at operating temperature of 55 degrees are the largest, which is 8975 kg, while the carbon emissions generated by high COP GSHP at operating temperature of 35 degrees are the smallest, which is 4739 kg. And it can be demonstrated that GSHPs are more environmentally friendly than NG boilers in most cases. Compared with the current period, in the future, the amount of carbon dioxide generated by using ground source heat pumps to provide the same energy will gradually decrease, even in 2050, carbon emissions will become negligible, making the house close to zero-carbon buildings. Compared with ground source heat pumps, the amount of carbon dioxide produced by natural gas boilers varies slightly between 2018 and 2050, and has always been very high. And the annual emission reduction in three different periods is shown separately in the Figure 7.

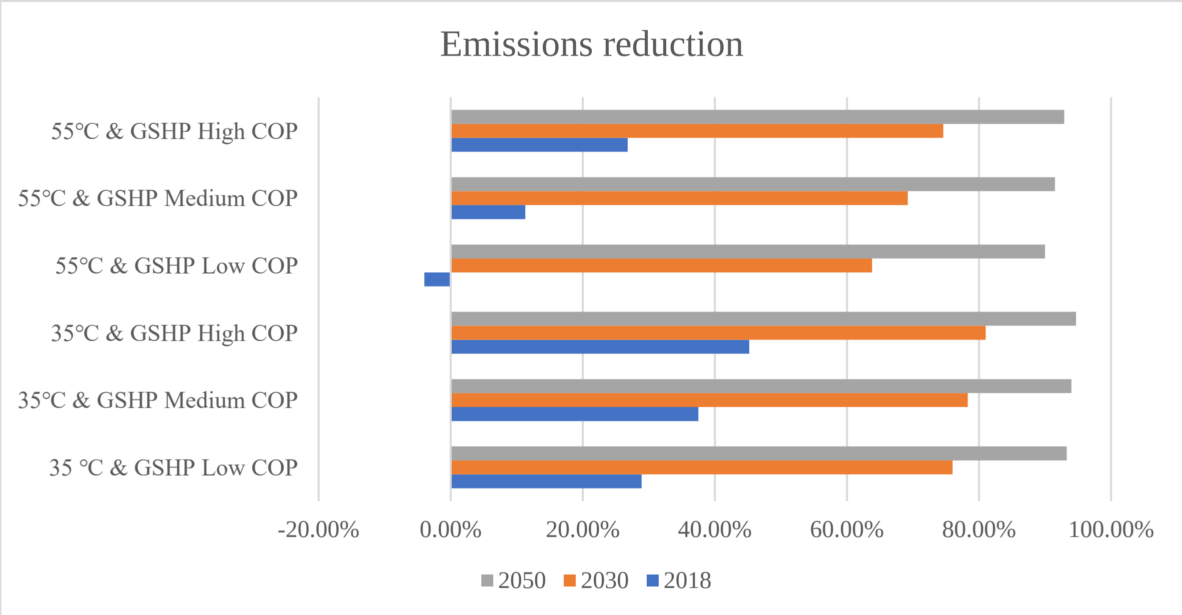


Figure 7. Annual emissions reduction from GSHPs in 2018,2030 and 2050, compared to a NG boiler (85% efficient), with different heating methods

Figure 7 shows that, the emissions reduction compared to a NG boiler are gradually increasing with the COP of GSHPs increases from 2018 to 2050. It can be found that the carbon emissions from heating with NG boiler change very little. While carbon emissions will be reduced by about 40% in 2030 and even 90 percent in 2050. The most carbon emissions reduction from using GSHPs replace NG boiler is 45.2% for current period. Moreover, it can be found that GSHPs with 35 ℃ operation temperature brings around 20%-30% additional reduction over the GSHP cases with 55 operation temperature. However, the carbon emissions of using GSHP was higher than using NG boiler when its COP is lower than 2.2. This suggests that when the GSHP system is operating at low COP (i.e., at peak demand), it is more carbon intensive than using the NG boiler. Moreover, when the operating temperature is reduced from 55 to 35 degrees, a 13% reduction is produced for the same ground source heat pump.

3.3. Comparison in Economic Costs

3.3.1 The price of electricity and gas

According to the methods shown in section 2.4, the price of electricity and gas from 2018 and 2050, shown in Figure 8, was predicted.

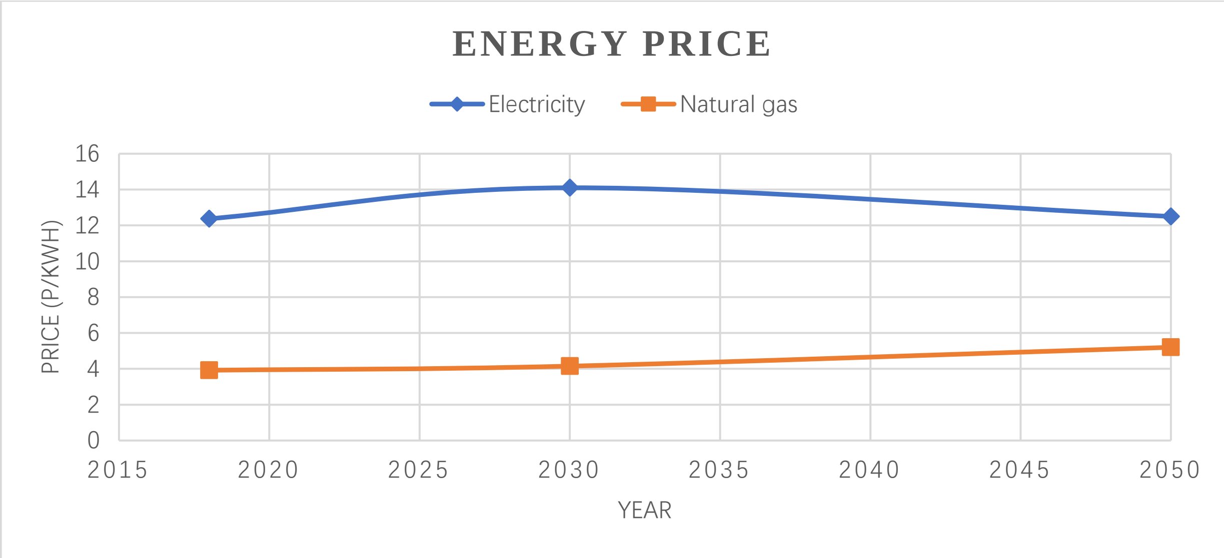


Figure 8. The predicted prices of electricity and natural gas from 2018 to 2050

From the Figure 8, it can be found that the average price of electricity and natural gas is 12.37 P/kWh and 3.92 P/kWh in 2018. Besides, the price of electricity bills will be cheaper in the future, while gas prices will be higher and higher. The price ratio of electricity to gas has gradually dropped from 3 in 2018 to about 2 in 2050.

3.3.2 Running Cost

Based on the energy prices, the annual fuel costs of each heating system in 2018 and were calculated using Equation 2 mentioned in section 2.4. And the detailed results are shown in Table 11. Moreover, the is Renewable Heat Incentive (RHI) payment for heat which they generated by a ground source heat pump was obtained and shown in Table 12.

Table 11. Annual energy costs in 2018

Year	Cases	Energy Costs (£)	
		Floor Heating (LWC 35 ℃)	Radiator (LWC 55 ℃)
2018	GSHP low COP	1427	2141
	GSHP Medium COP	1289.6	1830
	GSHP High COP	1129.9	1508.6
	NG boilers	1516.3	1516.3

Table 12. Annual Renewable Heat Incentive (RHI) payment in 2018

Year	Cases	RHI Subsidy (£)	
		Floor Heating (LWC 35 ℃)	Radiator (LWC 55 ℃)
2018	GSHP low COP	2228.7	3344.1
	GSHP Medium COP	2014.2	2858.9
	GSHP High COP	1764.8	2356.3

Moreover, the operating costs saving of installing ground source heat pumps instead of gas boilers throughout the year can be obtained by subtracting RHI subsidies from the energy costs consumed and are shown in the Table 13.

Table 13. Anuual operating cost saving versus gas boiler in 2018

Year	Cases	Running Cost Saving versus gas boiler (£/year)	
		Floor Heating (LWC 35 ℃)	Radiator (LWC 55 ℃)
2018	GSHP low COP	2316.7	2717.4
	GSHP Medium COP	2239.7	2543.1
	GSHP High COP	2150.1	2362.6

From the above three tables, it can be seen that when the operating temperature of the GSHP system is 35 degrees, the annual energy cost is lower than that of the NG boiler. However, when the operating temperature is 55 degrees, in the current period, the energy consumption cost of GSHP system will be higher than that of NG boiler. Besides, the Renewable Heat Incentive will provide 19.33 P/kWh for heat generated by a GSHP system and the annual payment for different kinds of GSHP in 2018 is between 1764.8 and 3344.1 due to the differences in energy demand.

As for the annual operating cost savings, after replacing gas-fired boilers with ground-source heat pumps, savings could range from 2,150 to 2,717 pounds a year in 2018. And the lifetime operating costs for each GSHP systems from 2018 to 2050 were calculated by using Excel in same method and are shown in Figure 9.

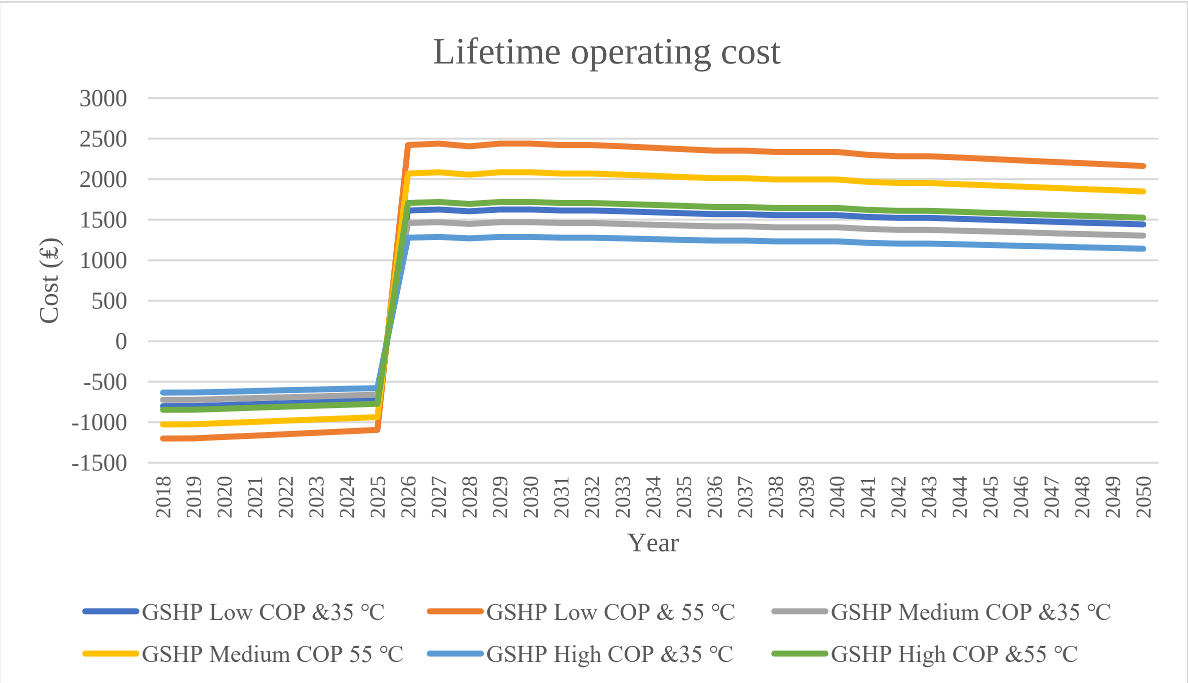


Figure 9. The lifetime operating costs for each GSHP systems from 2018 to 2050

From Figure 9, it can be found that in the seven years from 2018 to 2025, the use of ground source heat pump not only does not need to pay operating costs, but also can earn some subsidies from the

RHI, which helps to reach the break-even point faster. However, after RHI is not subsidized, the operating cost of GSHPs becomes very high, probably in the range of 1780 to 2400 pounds per year. It can also be found that when other conditions are fixed, the operating temperature of the GSHPs is reduced from 55 to 35 degrees, the annual operating cost will be reduced by about 250 pounds. For ground source heat pumps with different ecoefficiency of performance, their changing trend can also be clearly seen. With the increase of time, the annual operating costs of GSHPs will gradually become smaller.

3.3.3 Payback period

The general costs of a GSHP system which is related to its capacity, including the product cost, installation and emitter replacement costs were collected from literature review. In this research, for a required 12 kW GSHP, the general capital costs are list in Table 14 and the proportion of each part is shown in Figure 10. Besides the operating cost savings from 2018 to 2050 were calculated as well.

Table 14. Cost breakdown of the designed GSHP system

Item	Cost (£)	Source
Heat pump	8400	Domestic Ground Source Heat Pumps: Design and installation of closed-loop systems
Ground loop and Head pipe installation	11250	
Fittings	1500	
Total	21150	

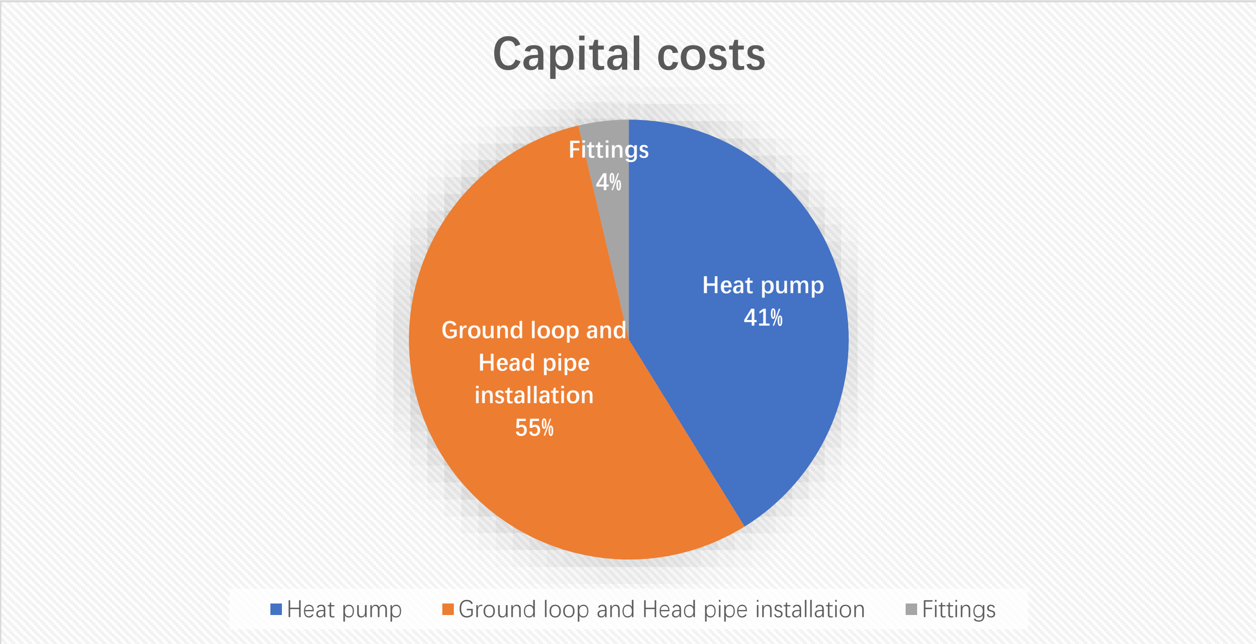


Figure 10. The proportion of each part in capital costs

The lifetime running cost savings versus NG boilers were calculated and are shown in Figure 11.

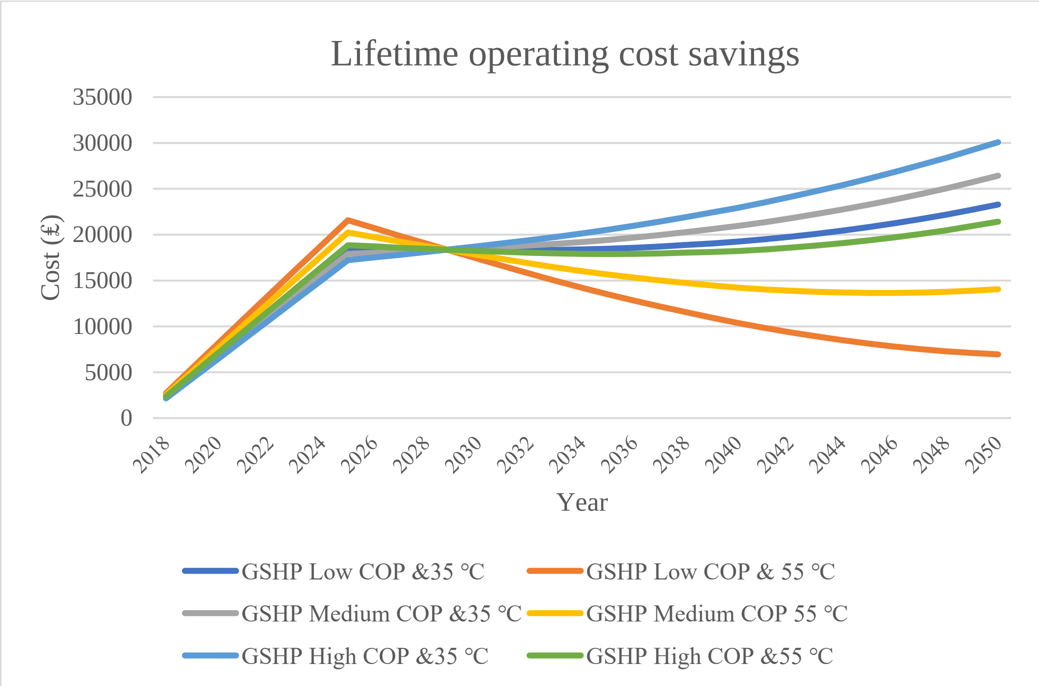


Figure 11. Lifetime operating cost savings versus NG boiler

By comparing the operation cost of ground source heat pump and gas boiler with different efficiency and operating temperature, it is found that the replacement of gas boiler with a ground source heat pump can save a lot of fuel cost within a few years after installation. After 2025, the operating cost savings of ground source heat pumps with medium or low COP in operating temperatures of 55 degrees show a downward trend. In other cases, the increase in operating cost savings of ground source heat pumps is smaller but still increasing. Therefore, it can be concluded that the ground source heat pump with efficiency higher than 3 can save money compared with the gas boiler. For example, when the high efficiency heat pump operates at 35 degrees, from 2018 to 2050, a total of 30086 pounds can be saved in heating.

Combining the operating cost savings and the capital cost, the payback period for installing different GSHPs can be obtained and is shown in Table 15.

Table 15. Payback period for different GSHP cases

Cases	Payback period (Year)	
	Floor Heating (LWC 35 ℃)	Radiator (LWC 55 ℃)
GSHP low COP	30	No
GSHP Medium COP	25	No
GSHP High COP	20	33

For low COP and medium COP ground source heat pumps, it is impossible to recoup the funds expended in an investment when the operating temperature is 55 degrees. But with the subsidies of RHI, the cost of using ground source heat pump has been reduced a lot. The shortest payback period in these six cases is 20 years when using high COP ground source heat pump operating at 35 degrees, and the longest return cycle is that low efficiency heat pump is used at 35 degrees, for 33 years.

3.4. Benefits

Through assuming the environmental and economic costs between GSHPs and NG boiler, the benefits of GSHPs are mainly in environmental aspects and were summarized as follows:

- Reduce the use of energy source because the COP of GSHPs can achieve about 4 times of NG boiler.
- The replacement of natural gas boilers by heat pumps supplied by electricity can reduce the carbon emission up to 45% in the current period, 63.8% to 81% in 2030 and 90% to 94.7% in 2050.
- In the future, as the market expands and technology develops, the cost of GSHP will be gradually reduced. With RHI subsidies, capital costs can be recouped as soon as 20 years.
- With the development of the times, the use of more new energy technologies has become a trend. The market of ground source heat pump will be bigger in the future.

The benefits of NG Boiler were mainly in economic aspects and were shown as follows:

- The maintenance costs were lower than using GSHPs in the current period or even in the future up to 2050 because the market is very large in the UK so that many technicians can be engaged in the maintenance of NG boilers.
- It doesn’t take replacement cost or a lot of time to change the heating systems because most of houses are still using NG boiler for heating in the UK.
- Compared with GSHPs, there is no need to bear the risk that capital costs cannot be recouped.

3.5. Results analysis

The capacity of the building’s heating equipment typically depends on the heating set point temperature and climate conditions. Hence the equipment needs to be sized to keep the building comfortable under the coldest conditions. Heating set point temperature was used to determine the peak heating load and to size the heating system accordingly. For the model house, the energy demand for GSHPs and NG boilers in heating season is different determined by the COP.

The effect of heating systems on the environment is mainly caused by the carbon emissions. And the detailed emissions were related to the COP of systems and the carbon emission factor of fuel. In fact, the difference in annual carbon emissions is due to the different ratio of the COP of system to carbon emission factor, so this ratio can also be used to assess the environmental cost of systems. Ground source heat pump can reduce more carbon emissions if the coefficient of performance can be improved and the carbon emission factors of electricity are reduced. In this research, through the method of controlling variables, several different cases of ground source heat pump and gas boiler were compared, and the final conclusion is basically in line with the idea before the study. However, due to the limitations of this study, although the overall trend is correct, there must be some errors in the results. As for the detailed error analysis, they will be mentioned in the next section.

For different types of heat pumps, the capital cost is different. Compared with natural gas boilers, it is possible to reduce the operating cost due to the high efficiency and RHI subsidies. Under the subsidy of the city government, the cost of using a ground source heat pump has been reduced a lot, and the use of natural gas will be strictly restricted in the future. It is possible that high taxes like tobacco and oil have led to higher costs. But the capital costs of GSHPs are still a big effect on the market becasue it may be not accepted easily by people although it can reduce the impact on the environment. This conclusion is also consistent with the views of many researchers.

3.6. Limitations Analysis

- The COP of GSHPs was assumed constant in the future because there is no method to predict exactly how much future development in the GSHP technology will affacts its efficiency. Therefore, this must lead to the results about the carbon emissions from GSHPs in the future are not very precise. Based on some existing liteature on the related studies, an error of about 10% may be generated due to this condition.
- In fact, it is difficult to analyze the effects of various factors on GSHP performance because it is

impossible to conduct a field trip. For example, many factors have been known to affect the performance of ground source heat pumps, and then affect carbon emissions and operating costs, but at this stage, the desired results can not be obtained due to the limitations of time, equipment and technology. And only theoretical analysis can be carried out by using the results of field tests conducted by previous organizations or researchers. Moreover, the performance of ground source heat pump in different places is different, but this study can only evaluate these two technologies in theory based on the established model.

- Future electricity and natural gas costs are predicted based on information from some energy websites and previous trends. Despite the desire to make the results more accurate, there are still some inconsistencies with the future. Therefore, the results of operating costs of geothermal heat pumps and gas-fired boilers in future service cycles can only be used as a reference to indicate a trend.
- The carbon emission factor of electricity in the future was predicted base on UK carbon emission targets may also be inconsistent with reality due to some external factors. Moreover, when assessing the environmental impact of the system, it is conceivable that many aspects can be considered, such as studying the environmental impact of ground loop on geological conditions and groundwater. In addition, power generation in the current period will also produce some other environmentally influential gases, such as CO, SO2 and NOx. These more relevant studies can further improve the assessment of the use of ground source heat pumps.
- In evaluating the benefits of GSHP systems, because of the limitation of this research direction, some aspects have not been taken into account. For example, in terms of refrigeration and noise. In the future, as global warming intensifies, indoor temperature may often be very high, and air conditioning will become very important. Compared to gas boilers, the use of ground source heat pumps eliminates the need to separately install air conditioners.

3.7. Future work

Because of the high cost of ground source heat pump, its use in residential houses is largely limited. In view of this situation, it is very important to design a suitable ground source heat pump. For example, the capacity of ground source heat pump should not exceed the highest heat load in the whole year. Meanwhile, suppliers need to find ways to reduce the capital costs of ground source heat pumps.

Replacing fossil fuels with electricity will further help achieve the goal of low carbon, because electricity can be seen as a clean energy in the future. As new energy technologies are used more and more, the carbon emission factor of electricity will become lower and lower. Therefore, GSHP as the most suitable heat pump for residential use, combined with some technologies such as PV, wind power and so on, helps to achieve zero-carbon building in an all-round way.

4. Conclusion

This research analysed the environmental impact and economic costs of both GSHPs and NG boilers for residential heating in the UK. Six GSHP cases and one mainstream NG boiler were selected as the object of this research and build these system models in IES VE. Besides, a general review of the literature about the research methods and conclusions in this field conducted by previous scholars were presented. Some data for reference in this research, such as COP, capital costs of GSHPs and carbon emission factors of UK power generation were also summarised in the section of literature review.

After completing all the steps, it was suggested that lower carbon emissions compared with NG boilers can be achieved in the current period if the COP of GSHPs is higher than 2.2. In the future, the carbon emissions reduced by using GSHPs will gradually increase because the carbon emission factor of power generation is gradually decreasing, and even reduce carbon emissions by 90% in 2050.

In addition, the operating costs simulations of GSHPs and NG boilers in their lifetime have been done. It was shown that the use of GSHPs can save money in most cases, but whether it can be achieved is also related to the COP of GSHPs and the price ratio of electricity to gas. Between 2018 and 2050, due to fluctuations in energy prices, the annual savings of GSHPs in operating costs versus NG Boilers are not constant, ranging from £89 to £387. Then RHI will provide a seven-year subsidy for residential houses, which is about 19.33P per kilowatt-hour. Combined with these data, it is concluded that for a 12 kW GSHP, its payback period is 20 to 33 years in the case of heating only.

Finally, the result analysis and limitations analysis were provided, giving some advice on the future work. In view of this situation, using solar panels to power GSHP may be a good way to help achieve the goal of low-carbon or zero-carbon buildings. And after installing the solar panels, the operating costs become very low, although the capital costs will become very high.

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