# Influence of GSHP System Design Parameters on the Geothermal Application Capacity and Electricity Consumption at City-Scale for Westminster, London

Yi Zhang, R. Choudhary[1], K. Soga
Department of Engineering, University of Cambridge, Cambridge, UK.

## Abstract

A city-scale renewable energy network for heating and cooling can significantly contribute to reduction of fossil fuel utilization and meeting the renewable energy targets. Ground source heat pump (GSHP) system is a technology that transfers heat stored over long periods to/from the ground to heat/cool the buildings. In particular, a vertical closed loop GSHP is a viable choice in densely populated urban areas. In this study, an ArcGIS-based simulation model has been developed to examine how many vertical closed loop GSHPs can be feasibly installed at city scale without overusing the geothermal energy underground. City of Westminster, in London, is used as a case study to identify and map areas where GSHPs can serve as a viable option for heating and/or cooling. A parametric study has been conducted to investigate the influence of how space heating and cooling demand is quantified on the potential utility of GSHP systems. The influence of COP variation during operation is also examined. The operational variation of COP influences the electricity consumption of the GSHP systems. Therefore, a comprehensive analysis including the capital cost, C/D ratio distribution, energy demand, and financial risk is highly recommended for district-level planning of GSHP systems.

KEY WORDS: GSHP; City Scale; Building Load Estimation; COP; Ratio of Capacity to Demand; Electricity Consumption

## 1 Introduction

As part of 2009 EU-wide action to increase the use of renewable energy, UK has committed to set 15% renewable energy target by 2020, which is a significant rise compared with approximate 2% in 2008. As a result, energy from renewable sources increased to 5.2% in 2013 (DECC, 2014a), but this proportion is still fay away from the target. In the United Kingdom, nearly half of the energy is used to produce heat. As a significantly important sector of energy demand, it is deemed that 12% of space heating demand must be generated from renewable energy sources by 2020, which is a sharp increase from around 2% currently (DECC, 2013). Therefore, a large-scale renewable energy network for heating can significantly contribute to net-zero energy districts, security of energy supplies, and meeting the renewable energy targets. Ground source heat pump (GSHP) is a technology to transfer heat stored over long periods to/from the ground to heat/cool the buildings. GSHP systems are mainly

[1] **Corresponding Author:** Dr. Ruchi Choudhary, Reader in Architectural Engineering, Engineering Department, University of Cambridge, Trumpington Street Cambridge CB2 1PZ; Office Phone: +44 1223 332689; email: r.choudhary@eng.cam.ac.uk

classified into two types: closed-loop system and open-loop system. An open-loop GSHP system extracts the ground water directly via a borehole and the water is pumped through a heat pump to complete the heat transfer, so a good aquifer underground is required by such system. In comparison, a closed-loop GSHP system, pumping an anti-freeze fluid through pipes buried in the ground, can be installed everywhere without considering geological conditions. According to the UK Environment Agency (EA, 2009), there were 8000 installed GSHP systems in total in 2009, and the number of open loops was only 300. Among all kinds of closed-loop GSHP systems, vertical loops are more popularly used in urban areas due to space limitations and their system efficiency (Kavanaugh & Rafferty, 1997). Therefore, the vertical closed GSHP is potentially good option for city scale planning. In the GSHP design, the sizing of ground heat exchanger (GHE) is a key feature (Shonder and Hughes 1998). The sizing process requires the following as input parameters: heating & cooling demand of the building, ground thermal properties, ground temperatures at relevant depths, and heat pump efficiency. In most cases, GSHP designers consider these as exogenous and fixed parameters. In reality, there can be large deviation from design values in heating & cooling demand and heat pump efficiency (Hu, 2009; Banks, 2012; Garber et al., 2013; DECC, 2014b) .

In this study, an ArcGIS-based simulation model is developed to examine how many vertical closed GSHPs can be feasibly installed at city-scale, without overusing the geothermal energy underground. The simulation model outputs the ratio of capacity to demand (C/D ratio) distribution map for the city. The model is demonstrated through the analysis of GSHP potential in the City of Westminster in central London (Zhang et al., 2014). This model was built by embedding a GSHP design code (written in Python) within the ArcGIS environment (described in Section 3.1). Four spatial datasets are required as inputs to the model: the heating and cooling demand per building, thermal conductivity of soil, thermal diffusivity of soil, and ground temperatures. These four inputs can influence the design of the borehole length, and in turn influence the geothermal capacity distribution layout. Among these four, thermal conductivity, thermal diffusivity and ground temperatures were quantified according to the geological condition of Westminster referring to the British Geological Survey. This is the most high-resolution and reliable spatial dataset that can be obtained for underground thermal properties of London. As for the heating and cooling demand, the total annual amount of each building was initially estimated according to annualized benchmark standards per building type. This approach assumes constant operation during heating and cooling months. Although this approach is often adopted by majority of commercial GSHP design software, studies have shown that monthly and hourly variations in heating/cooling demand can lead to a more precise result by reducing the possibility of over or under sizing (Chiasson et al. 2005; Banks 2012). The influence of heating/cooling demand calculations on C/D ratios is therefore tested in this study.

In addition to the spatial datasets above, the heat pump efficiency is also an important parameter influencing the energy efficiency of a GSHP system. The heat pump extracts the heat through ground heat exchanger (GHE) and delivers the heat to/from the building for heating/cooling. In this current study, the heat pump capacity was selected to cover 100% of the heating and cooling demand for each building and the related parameters such as inlet and outlet liquid temperatures were estimated according to the typical empirical values provided in the literature (Kavanaugh & Rafferty, 1997; DECC, 2008). The key parameters to indicate the heat pump efficiency are COP, coefficient of performance for heating mode, and EER, energy efficiency ratio for cooling mode. In the UK, most of the domestic buildings have only heating demand, so COP is more often used to characterise a heat pump's efficiency. COP is ratio of *H*, the total heat output from heat pump, to *E*, the electrical energy required to power the heat pump. For most of space-heating GSHPs, a COP is designed to be at least 3.0, and probably approaching 4.0 (Banks, 2012). However, any given heat pump does not have a fixed COP value under operation as this will depend on the operation conditions, including heat pump cycling, loop temperature, pump penalty, auxiliary electric heat and equipment malfunctioning (Davis, 2013). Therefore, an actual COP under operation deviates from the design value, and this influences the net electricity consumption by the GSHP system.

Many studies have investigated the two parameters: heating/cooling demand and COP value of the heat pump, but they mainly concentrate on their influences on the design and operation of a single GSHP system. This paper focuses on the parametric analysis on GSHP application at city-scale for the case study of Westminster, London. The analysis specifically investigates the influence of heating/cooling demand estimation on the ratio of capacity to demand (C/D ratio) distribution map, and also the influence of COP difference between design and operation on net electricity consumption and cost. To achieve this goal, heating and cooling demands with annual, monthly and hourly variations, and also the COP values under operation for all the buildings in Westminster were firstly estimated. All the prepared data was then input into the city scale model to obtain the simulation results for parameter analysis.

## 2 Current Parameter Estimation Approaches

### 2.1 Heating and Cooling Demand Calculation

Heating and cooling demand estimation is very important to size a GSHP system correctly. Indeed the heat pump capacity and the total length of the GHE are generally selected based on the peak load. Without sufficient monitoring data, a building's peak heating and/or cooling demand is usually estimated by using commercial simulation software packages, benchmark standards, or empirical equations. For more complex or larger projects, a building design engineer usually calculates the total demand using hourly dynamic simulations (eg. IES-VE, energyplus) and gives the results as input to a

GSHP designer. For small scale projects, such as domestic buildings, the loads are usually estimated by a GSHP designer using rules of thumb (Garber, 2014).

Some authorized guidelines are often used to calculate the building load in the UK, such as BSRIA 2003, CIBSE 2004 & 2008, SAP 2010. These guidelines are estimated on the basis of actual heating and cooling demand of typical building types. The actual load is used to provide total annual heating and cooling demand per floor area for each type. 'Degree days' is another simplified method to estimate the building load based on the total conductive heat loss calculation. The heating demand is obtained by calculating the total area between the real temperature curve and the baseline value, which can be the comfortable indoor living temperature, for a required period. The value indicates both severity and duration of cold weather and is expressed in the 'degree days concept' (Carbon Trust, 2006). In the UK, the common baseline heating temperature is around 15.5 ℃. The cooling demand is calculated by using 'cooling degree days'. This is calculated based on the period during which the outside air temperature is higher than a certain baseline value (Banks, 2012). If more detailed demand is required including hourly and seasonal variation, dynamic energy simulation software packages can be used to calculate the demand with consideration of building geometry, operational requirements, and surrounding environment conditions.

In this particular study, the heating and cooling demand was calculated using three levels of time-resolution: annualised total per building type, monthly total per building type, and hourly demand per individual building. The three approaches are here-on referred to as annual, monthly, and hourly respectively (described in Section 3.2). Results were compared to investigate the influence of demand calculation method on the results.

## 2.2 COP measurement

COP is a key parameter influencing the energy efficiency of a GSHP system. However, a given heat pump does not have a fixed COP due to the operation conditions, so measuring COP value in the operation is an effective way to examine the performance of the system.

Reviewing the electric bills with a regular frequency is a common way to assess the system performance of residential systems and a lower electric bill value indicates higher operation efficiency. However, the measurement is not usually reliable as it is difficult to remove other factors contributing to the overall electrical consumption, such as lack of baseline for new buildings, no special electric meter for the GSHP system and delayed report from the landowner. Compared with relying on the electric bills, monitoring the system is a more efficient way to diminish the problems above and provide more reliable measurements (Davis, 2013). As COP is ratio of $H$ to $E$, the heat output and the consumed electricity can be monitored by heat meters and electricity meters, respectively. Such data has been collected in a certain time interval, recorded by web loggers and sent back for analysis (DECC, 2014b). The heat output can also be indirectly obtained by calculation based on the measurements of inlet and outlet temperature of the heat pump, total fluid flow to the pump, heat capacity and density of the ground loop fluid. In this case, instruments such as thermistors and turbine meter are required accordingly (Puttagunta et al. 2010).

For the analysis presented in this paper, a monitored COP distribution report produced by DECC in 2014 was used for assigning actual operation COP values to the buildings. This report was developed from the Renewable Heat Premium Payment (RHPP) heat pump metering programme, which aimed to examine the performance of real-life systems and to diagnose the most common sources of the problems. Data was provided from all parts of the UK in quasi-real time with collection over two-minute period. Accuracy and data completeness were treated seriously in this programme, and both of them achieved high levels, which are +/-10% accuracy and 90% data completeness. To obtain the COP values, the heat output and the heat pump electricity consumption were measured with heat and electricity meters. The meter installations were carefully tested in the lab and then operated in the systems. In addition, a website was used by the project team to perform semi-automated checks on the data to identify if the equipment was correctly installed or well worked. After data analysis, a COP frequency distribution chart for GSHP systems was given as one result (DECC, 2014b). This chart is used for allocating COP values at a large scale.

## 3 City-scale GSHP System Simulation for Parameter Analysis

### 3.1 Model for Heating and Cooling at City Scale

An ArcGIS-based simulation model with embedded GSHP design code was developed to estimate the geothermal potential underground and to evaluate the allowed GSHP capacity with the land use restrictions for the City of Westminster, London (Zhang et al, 2014).

The embedded GSHP design code in the model is based on the Cylinder and Line Source Method, which has been considered to be most accurate model through comparison with calibrated data from actual operation (Shonder and Hughes, 1998) and widely used to estimate the length of the ground heat exchanger (GHE) by current commercial software packages. Both heating and cooling are considered in this code, and the main equations related to the design calculation are as follows: $L_h$ for heating;

$$L_h = \frac{q_a R_{ga} + (q_{lh} - \overline{W}_h)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \qquad (1)$$

and $L_c$ for cooling (Kavanaugh and Rafferty, 1997).

$$L_c = \frac{q_a R_{ga} + (q_{lc} - \overline{W}_c)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \tag{2}$$

where $Fsc$ is the short-circuit heat loss factor, $PLFm$ is the part-load factor during design month, $q_a$ is the net annual average heat transfer to the ground (W), $q_{lh}$ is the building design heating block load (W), $q_{lc}$ is the building design cooling block load (W), $R_{ga}$ is the effective thermal resistance of the ground in annual pulse (mK/W), $R_{gd}$ is the effective thermal resistance of the ground in daily pulse (mK/W), $R_{gm}$ is the effective thermal resistance of the ground in monthly pulse (mK/W), $R_b$ is the thermal resistance of borehole (mK/W), $t_g$ is the undisturbed ground temperature (K), $t_p$ is the temperature penalty for interference of adjacent boreholes (K), $t_{wi}$ is the liquid temperature at heat pump inlet (K), $t_{wo}$ is the liquid temperature at heat pump outlet (K), $W_h$ is the power input at design heating load (W), and $W_c$ is the power input at design cooling load (W).

Four spatial data maps were required as inputs for the model, which are heating ($q_{lh}$) and cooling demand ($q_{lc}$), thermal conductivity($k_g$), thermal diffusivity($\alpha_g$) and ground temperature($t_g$). In Equations 1 and 2, $R_{ga}$, $R_{gm}$ and $R_{gd}$ were calculated based on thermal conductivity ($k_g$) and thermal diffusivity ($\alpha_g$). The dimensionless Fourier Number ($F_o$) is required to relate with the time of operation $(\tau)$, outside pipe diameter ($d$) and the thermal diffusivity of the ground $(\alpha_g)$. This relationship was modified to calculate the equivalent thermal resistance for three different heat pulses (Kavanaugh and Rafferty, 1997). In other words, the GSHP was modelled based on three heat pulses, for example, in the annual demand scenario, a 30-year pulse, a one-month pulse, and a twelve-hour pulse. All the time units were transferred to days and the Fourier numbers were then computed with Equation 3.

$\tau_1$=3650days, $\tau_2$=3650+30=3680days, $\tau_f$=3650+30+0.25=3680.25days

$Fo_f = 4\alpha_g \tau_f / d^2$,

$Fo_1 = 4\alpha_g (\tau_f - \tau_1)/d^2$, and

$$Fo_2 = 4\alpha_g (\tau_f - \tau_2)/d^2 \tag{3}$$

The thermal resistance during each heat pulse was determined according to Equation 4, where G-factor for each Fourier value was looked up from a G-factor graph for Cylindrical Heat Source (Kavanaugh and Rafferty, 1997).

$$R_{ga}=\frac{G_f-G_1}{k_g};R_{gm}=\frac{G_1-G_2}{k_g};R_{gd}=\frac{G_2}{k_g} \quad (4)$$

The spatial distribution of ground thermal conductivity and diffusivity across the City of Westminster was estimated based on the geological map and the thermal property look-up table. The geological map of Westminster was obtained from the British Geological Survey (BGS) geological map of London. There were 42 types of soil in total. This map was divided into grids with size of 50m×50m in east-west and north-south directions and 1m in the vertical direction. In this way, a 2D+height map showing the soil type distribution was developed. For each type of soil, its thermal property assignments (including the thermal conductivity and the thermal diffusivity) are derived from the data logs of site investigation work in London provided by BGS. Within 150m depth, the average thermal property value of all the grids in the same horizontal position was estimated to develop the distributions of the thermal conductivity and the thermal diffusivity. For the ground temperature, the measured ground temperature of London was used in the design. According to the well data from Headon et al. (2009), the ground temperature in the design was set to be 13.0°C as the average ground temperature value within the depth of 150m. In addition to the spatital data, related conditions and assumptions for the GSHP and the borehole are listed in Table 1. The calculation of heating and cooling demands for all the buildings in Westminster are described in the next section.

Previous work has shown that, in principle, the underground can fully satisfy the heating and cooling demands of all buildings in the city of Westminster (Zhang et al, 2014). However, in reality the availability of land space allowed for borehole installation becomes a key restriction for GSHP capacity at city scale. In this model, two scenarios were considered: (a) under building – within the land-area of the existing building, and (b) around the building – on the buffer area with the building boundary as the midline. The spacing between any two boreholes was fixed at 6 metres to avoid thermal interference, as per the MIS (DECC, 2008). The borehole length was set to be 150m according to the standard in UK. The ratio of capacity to demand (C/D) is calculated by dividing the maximum possible number of boreholes within the building's land area by the required borehole number for the heating and cooling demand.

**Table 1 Conditions and Assumptions in BHE Design**

| Parameter | Unit | Value | Justification |
|---|---|---|---|
| Coefficient of Performance(COP) | / | 3.3 | Typical Value |

| | | | |
|---|---|---|---|
| | | | (Kavanaugh and Rafferty, 1997) |
| Energy Efficiency Ratio (EER) | / | 4.2 | Typical Value (Kavanaugh and Rafferty, 1997) |
| Short-circuit Heat Loss Factor ($F_{sc}$) | / | 1.04 | Typical Value (Kavanaugh and Rafferty, 1997) |
| Liquid Temperature at heat pump inlet for Heating($t_{wi}$) | K | 278.5 | Chosen Design value |
| Liquid Temperature at heat pump outlet for Heating($t_{wo}$) | K | 275.0 | Estimate based on typical temperature drop from Kavanaugh and Rafferty, 1997 |
| Liquid Temperature at heat pump inlet for Cooling($t_{wi}$) | K | 300.0 | Chosen Design value |
| Liquid Temperature at heat pump outlet for Cooling($t_{wo}$) | K | 308.0 | Estimate based on typical temperature drop from Kavanaugh and Rafferty, 1997 |
| Minimum Borehole Spacing | m | 6 | MIS (DECC,2008)[a] |
| Borehole Diameter | mm | 130 | MIS (DECC,2008)[a] |
| Pipe Diameter | mm | 32mm OD SDR-11 | MIS (DECC,2008)[a] |
| Thermal Conductivity of Pipe | W/m.K | 0.420 (PE 100) | MIS (DECC,2008)[a] |
| Pipe Centre-Pipe Centre Shank Spacing | mm | 52 | MIS (DECC,2008)[a] |
| Thermal Transfer Fluid | / | 25% Mono Ethylene Gylcol | MIS (DECC,2008)[a] |
| Thermal Conductivity of Thermally Enhanced Grout | W/m.K | 2.4 | MIS (DECC,2008)[a] |
| Borehole Thermal Resistance | m.K/W | 0.1 | MIS (DECC,2008)[a] |

[a]MIS (Microgeneration Installation Standard), DECC (Department of Energy and Climate Change, UK) (2008)

## 3.2 Annual, Monthly and Hourly Heating and Cooling Demand

The estimation of heating and cooling demand is a critical parameter in the design of GSHP systems. There is a large variation in the methods used by GSHP designers to quantify the demand. For the purpose of quantifying the extent to which the geothermal capacity can be influenced by this feature, the heating and cooling demand was estimated using three common approaches: annual, monthly, and hourly.

In the annual method, the intensity of heating and cooling demand per building type (in kWh/m2 per year) was gathered from DECC certificates (compiled and released by the UK Centre for Sustainable Energy), Chartered Institution of Building Services Engineers Guide F and TM 46 (CIBSE, 2004, 2008) and 2011 energy distribution charts (EDCs). The design heating block load per building ($q_{lh}$ in kW) was estimated by multiplying the heating demand per building type in kWh/m2 per year with the floor area of a building and dividing by the number of heating hours in a year (2160 h in this case, assuming 12 h of heating per day for half the year).

Monthly estimates for space heating and cooling demand was quantifying using the information on monthly heating and cooling degree-days from the NASA Surface meteorology and Solar Energy Data Set for the distributed energy system location (ASDC, 2013). The heating and cooling degree-days were normalised and used to disaggregate the annual demand totals into monthly demand totals.

For the hourly calculations, each of the 95,817 building was individually simulated using EnergyPlus V8.0, developed by the US Department of Energy (DOE 2013). The parameters associated per building (geometry, thermodynamic properties, and operational schedules) were obtained from high-resolution data-sets provided by UK DCLG. The detailed procedures behind this work are not yet published but more information can be found at www.eeci.cam.ac.uk/cimo. The result from this step is hourly heating and cooling profiles for each building in the city of Westminster.

### 3.3 COP value distribution under operation

The RHPP heat pump metering report (DECC, 2014b) gave a COP frequency distribution under operation from the monitoring results. These sets of data were obtained from the metering equipment installed in the private householder and social landlord part of the scheme from all parts of the UK. With this given frequency distribution, a new chart (Figure 1) was developed based on the total number of buildings in Westminster (95,817 in total) and all the COPs were randomly assigned to each system as the actual operation values. From the COP distribution for Westminster shown in Figure 1, it can be seen that the most frequent value is around 2.7 and this is smaller than the design value of 3.3. In addition, there are some buildings with very low COP below 2.0 possibly due to low performance of the GSHP or measurement error of the sensor, but these only account for around 10%.

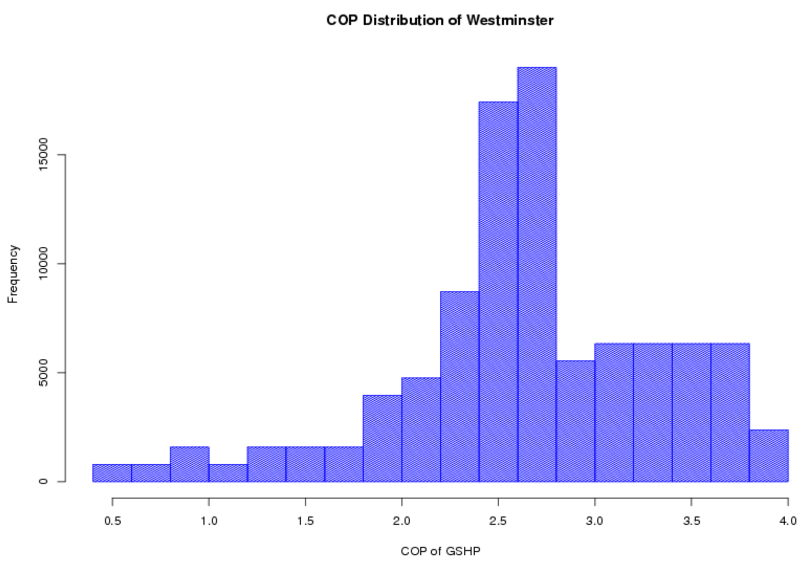



Figure 1 COP Frequency Distribution under Operation for All the buildings in Westminster

## 4 Results and Discussion

According to the UK Map database (GIG, 2010), there are ~95,817 buildings in total within the city of Westminster. This total number is made up of 42% of residential buildings, 32% of offices, 9% of retails and 17% of other types including hotels, schools, hospitals and leisure facilities. The land use type distribution of Westminster is shown in Figure 2. For all the buildings, the information such as floor area, height and usage is provided. Most of buildings are low-rise with only five floors or fewer (80.7%).

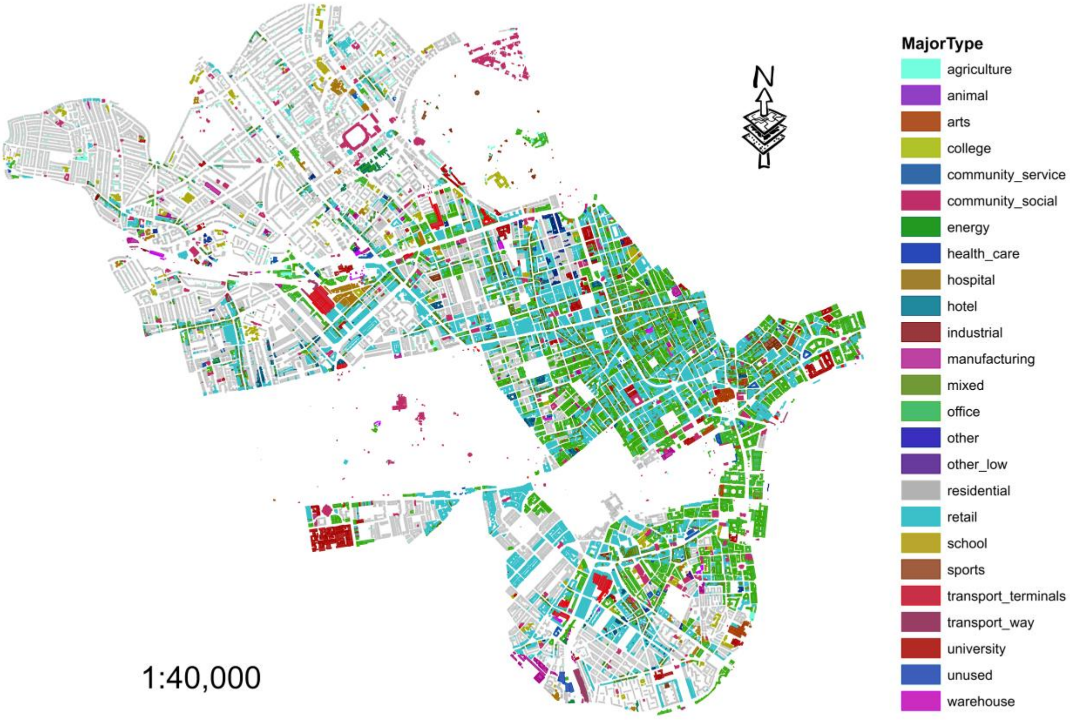
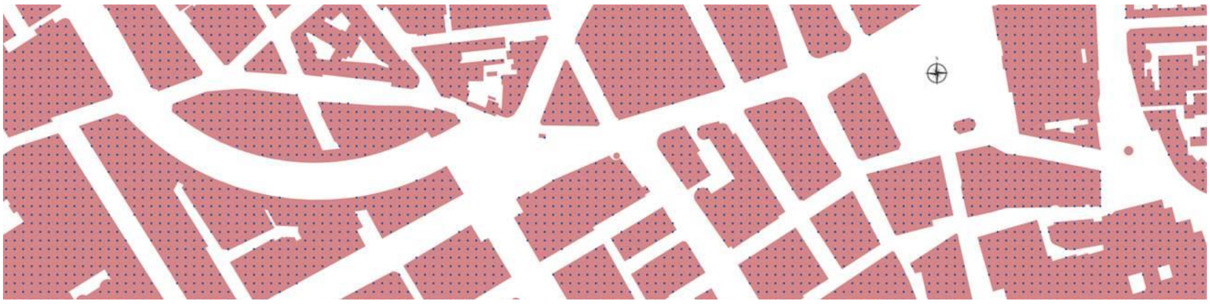
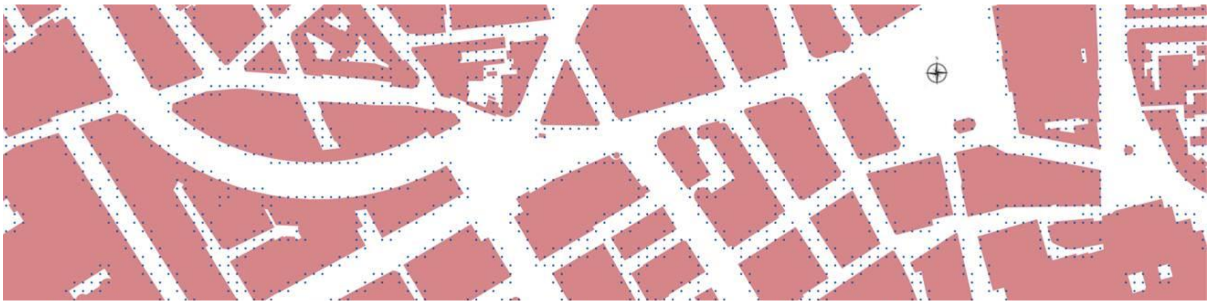



Figure 2 Land Use Type Distributions of Buildings in Westminster

Two scenarios (Figure 3) were considered in this study. For scenario 1, the boreholes were installed just under buildings, so the permitted space for installation of each building is the shape area in the map. This was taken as a reference case (due to the difficulty to drill under the existing buildings in reality). For scenario 2, the boreholes were installed around buildings within a buffer area, which is within 3m of the edge of a building, both away from and under it. This buffer area size can be adjusted under additional conditions and restrictions.



(a)



(b)

Figure 3  Borehole Allocation Map of a Corner of Westminster; Scale 1:2000 (Zhang et al. 2014）

(a) Scenario 1, Borehole under Buildings   (b)Scenario 2, Borehole around Buildings

4.1 Influence of Building Load Estimation on C/D ratio Distribution

For the design based on the annual building load, both heating and cooling duration were assumed to be six month per year, 30 days per month, and 12 hours per days. For the design based on the monthly building load, a seasonal load variation from January to December was also considered. For the design based on the hourly building load, a detailed distribution in hour was used for quantifying the peak and total loads to calculate daily and monthly part-load factors. These three methods of load estimation influence the resulting spatial distribution of the capacity versus demand (C/D) ratio in both scenarios.

Figure 4 compares the C/D ratio frequency distributions considering the total number of buildings in Westminster based on the three load estimation methods in Scenario 1. The C/D ratio represents the ratio of capacity to demand, so the bigger the better. In the results, green colour stands for the ratio of 100% or more, which means the heating and cooling demand can be fully satisfied by its own capacity. Yellow colour and red colour indicate 50%~100% and 0%~ 50%, respectively.  The grey colour takes accounts for 2% of the buildings without any heating or cooling demand. The percentage value written on the colour indicates the proportion of buildings for each C/D ratio range in Scenario 1 (Figure 4). Figure 5 shows the spatial distributions of C/D ratio based on annual and hourly estimation methods under Scenario 1. The C/D ratio frequency distributions resulting from monthly and annual calculations are quite close to each other, but the hourly case is varied with a reduced percentage of buildings that can fully satisfy its own demand. It can be seen that, the coverage area of green colour becomes significantly reduced in the hourly case compared with the annual estimation case. However, the proportion of buildings that can only provide less than 50% of demand (red colour in Figures 4 and 5) does not vary much from case to case.

Figure 6 compares the C/D ratio frequency distributions based on the three load estimation methods under Scenario 2. In Scenario 2 (Figure 6), the difference in C/D ratio distributions between the three estimation methods shows a similar trend to Scenario 1, but the percentage drop of buildings with ratio of more than 100% from annual to hourly calculations (from 66.6% to 61.6%,) is much smaller than in Scenario 1(from 51.0% to 37.3%, Figure 4). Figure 7 shows the spatial distributions of C/D ratio based on annual and hourly estimation methods under Scenario 2. It can be also seen that the change of spatial colour distribution in Scenario 2 (Figure 7) is slighter than Scenario 1(Figure 5).

Under both of scenarios, the C/D ratio distributions due to annual and monthly calculations are nearly the same, mainly because the operation time in the annual calculations is set to be only six months while the operation in monthly calculations follows the outdoor temperature and therefore the system can be in operation throughout the whole year. This makes the peak monthly loads in these two cases approaching to each other. In addition, the operation days and operation hours are assumed to be the same in both monthly and annual calculations, so the final design results are expected to be similar. However, in the hourly calculation case, the peak hourly and daily loads are greater than the ones in the other two cases, so the required heat pump capacity is larger in the design and it is more difficult to satisfy with the limited land space. This is the main reason to cause the smaller green colour proportion in the hourly case for both scenarios.

By comparing Figures 4 and 6, it can be also found that the change between cases in Scenario 2 is slighter than in Scenario 1, because the available space for borehole installation is larger for ‘Boreholes around Buildings’ and the capacity is greater accordingly. The reason to cause this difference is mainly because there are many long and narrow buildings in Westminster. For these buildings, more space is available for installing boreholes around them than underneath them (Zhang et al, 2014).

For the buildings in Westminster, the influence of the variation in building load estimation is greater under Scenario 1 than under Scenario 2. For both of scenarios, the annual and monthly estimations produce close results, but the hourly estimation leads to a comparatively lower capacity. Although the hourly estimation is the most accurate way to assure the peak load can be satisfied, the peak may only occur on a very few days (Banks, 2012). Therefore, it may make sense to consider the capital cost, C/D ratio distribution and also the building load satisfactory together to produce a wise choice. As for the days with unsufficient supply from GSHPs, other supplementary sources of heat can be employed.

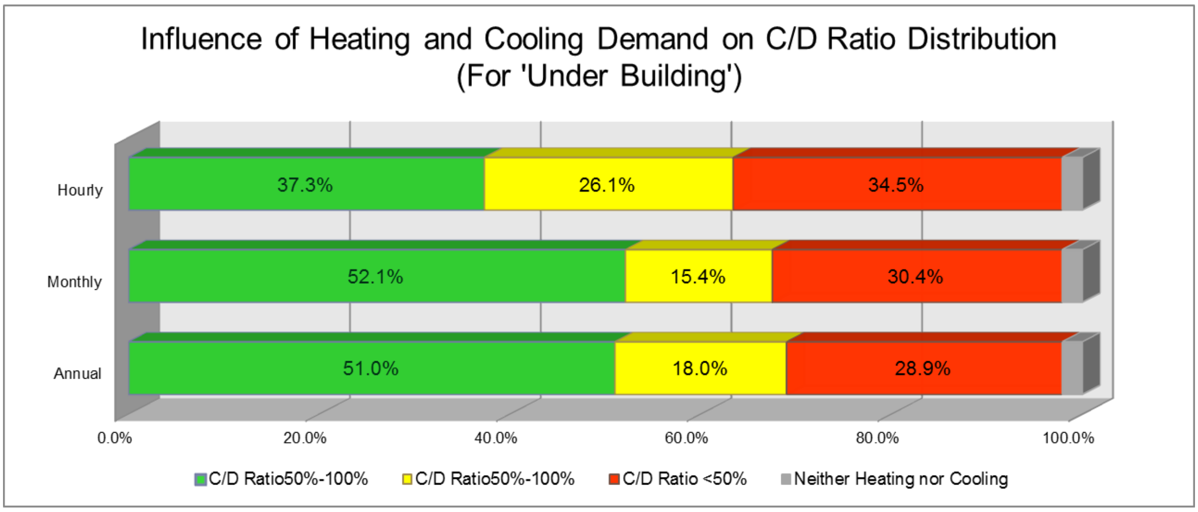
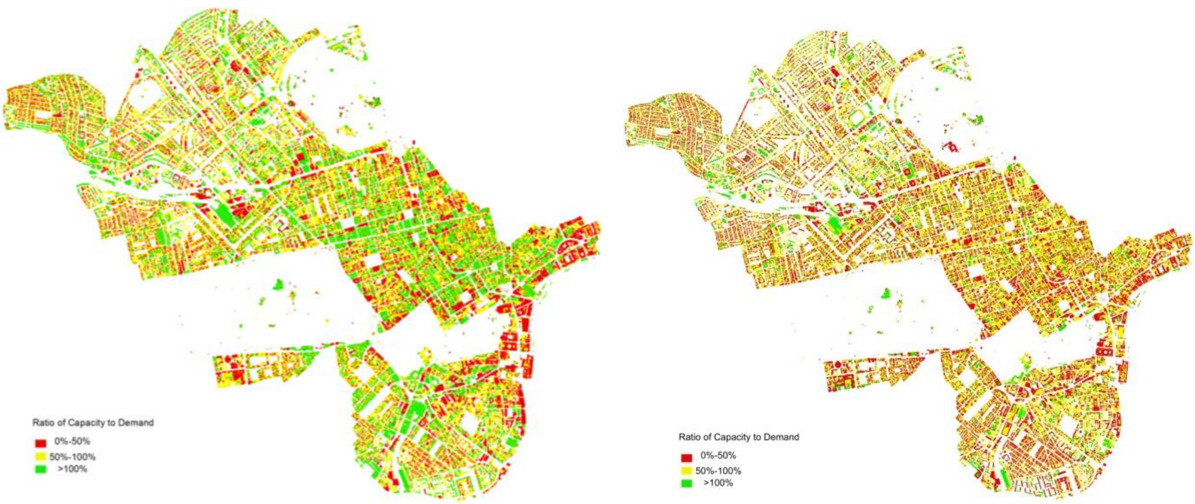



Figure 4  C/D Ratio Frequency Distributions with Various Building Load Estimation Methods under Scenario 1




(a)  Annual Building Load

(b)  Hourly Building Load

Figure 5  Spatial Distributions of C/D Ratio with Various Building Load Estimation Methods under Scenario 1

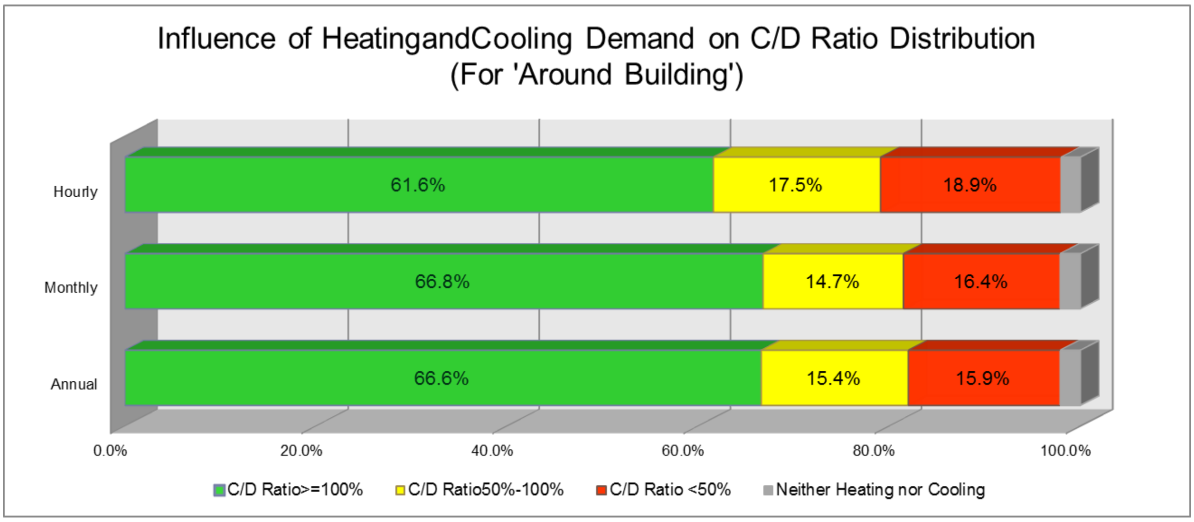
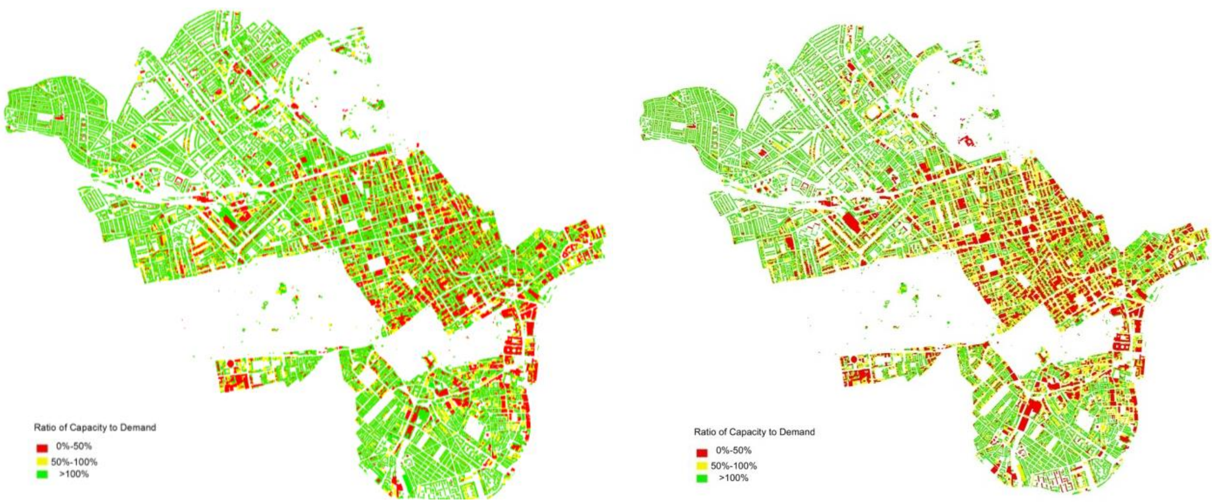



Figure 6  C/D Ratio Frequency Distributions with Various Building Load Estimation Methods under Scenario 2




(a) Annual Building Load (b) Hourly Building Load

Figure 7  Spatial Distributions of C/D Ratio with Various Building Load Estimation Methods under Scenario 2

## 4.2 Influence of COP Difference between Design and Operation on Electricity Consumption

The expected electricity consumption with GSHP systems are calculated based on the design COP and the maximum heating and cooling supply for each building under the allowed capacity. This, so called, *design electricity consumption* was calculated based on the annual heating and cooling estimation method. However, COP usually changes when a GSHP system is operating. Thus a COP distribution chart was developed for Westminster (see Figure 1 and section 3.3). The *operational electricity assumption* to support the same expected building load was calculated by randomly sampling the COP of systems from Figure 1. The electricity bill per unit floor area is used as the indicator to show the difference between design and operation. The electricity price used in this analysis is 17.2 pence per kWh, which is the average of prices in 2013 in the UK from the six big companies including E.ON, EDF, nPower, British Gas, Scottish and SSE (Compare my Solar, 2013).

Figure 8 compares the frequency distribution of the design and operational electricity bill under Scenario 1. It can be seen that the design electricity cost per unit floor area is densely distributed within the range of £0-£6, but the operational electricity cost has a wider spread covering higher ranges. Figure 10 compares the frequency distribution of design and actual electricity bill for Scenario 2. Under this scenario, more than half of the buildings have the cost between £4 and £6, and the others are concentrated in the range of £0-£4. The difference between these two scenarios is because more buildings with relatively intense heating and cooling load are satisfied under Scenario 2 (there is more permitted space for borehole installation around buildings under scenario 2). For these buildings, there is a normal electricity cost in Scenario 2, but there is less or even no cost in Scenario 1.

Figure 9 shows the frequency distribution of electricity bill increase under Scenario 1. A positive number on the horizontal axis means the electricity cost increases from the design stage to the operation. In contrast, a negative value means the electricity cost decreases. From this figure, it can be found that approximately 55% of the buildings have a cost increase between £0 and £1 per unit area, and only around 10% of the buildings have the change of more than £2. Figure 11 presents the frequency distribution of electricity bill increase under Scenario 2. The electricity cost change under Scenario 2 shows nearly the same distribution as Scenario 1 with around 50% between £0 and £1 and 10% more than £2. These 10% of buildings with electricity cost increase of more than £2 in both of scenarios exist because there is 10% of COPs lower than 2.0 in the COP allocation due to low performance of the GSHP or measurement error of the sensor. These kinds of GSHPs need to be checked as soon as possible for repairing or replacement. Therefore, it can be summarized that, for both Scenario 1 and Scenario 2, the electricity cost increases are mainly (around 90%) from £-1 to £2 and the largest portion is concentrated within the range of £0-£1.

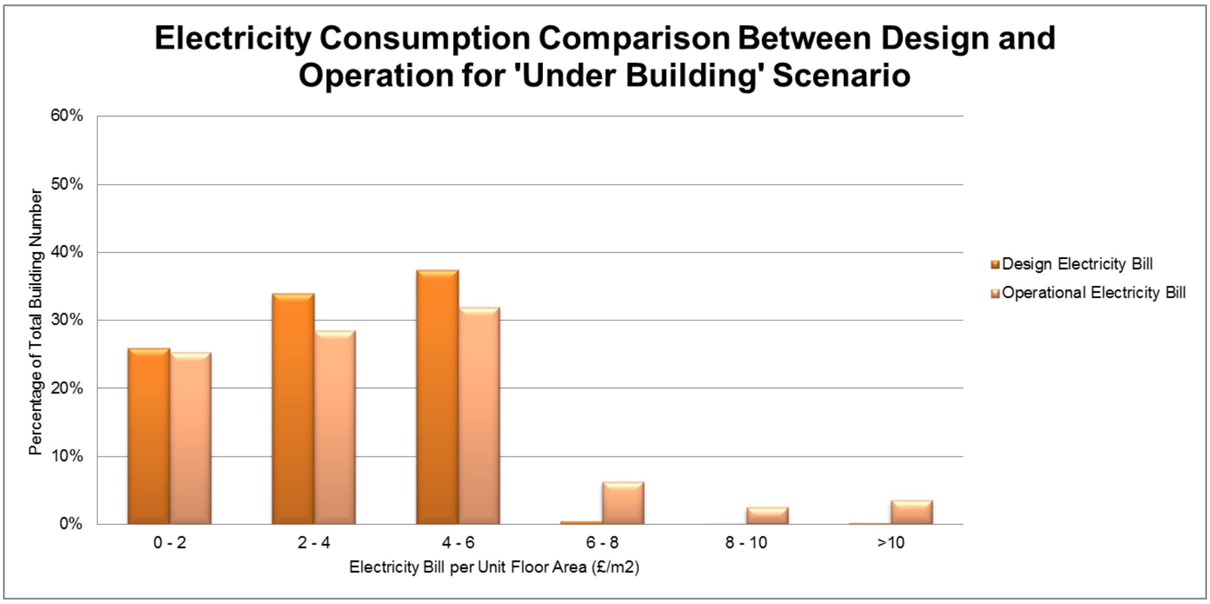



Figure 8  Electricity Consumption Comparison between Design and Operation under Scenario 1

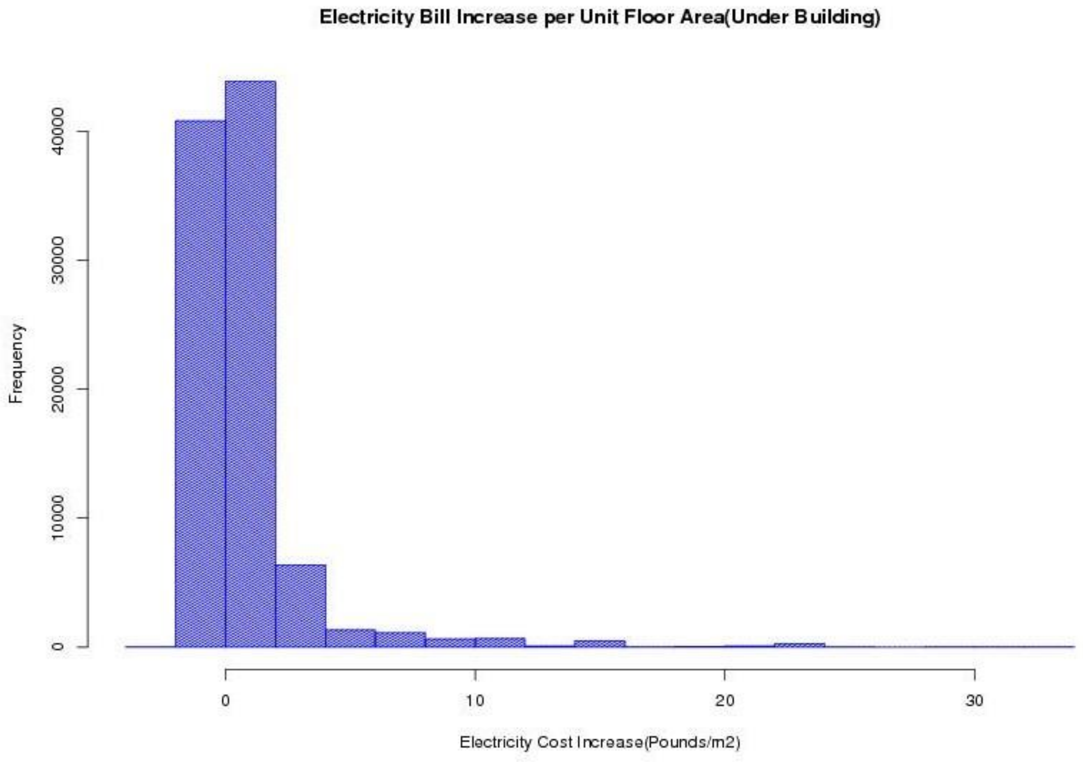



Figure 9  Electricity Cost Increase from Design to Operation under Scenario 1

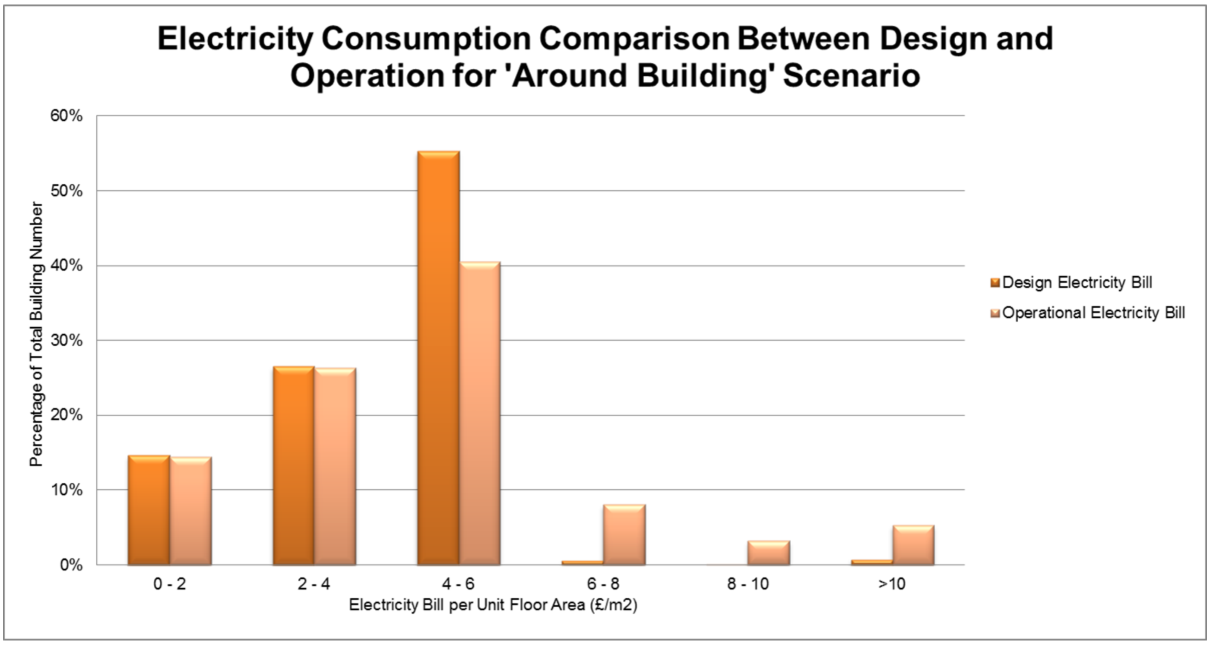



Figure 10  Electricity Consumption Comparison between Design and Operation under Scenario 2

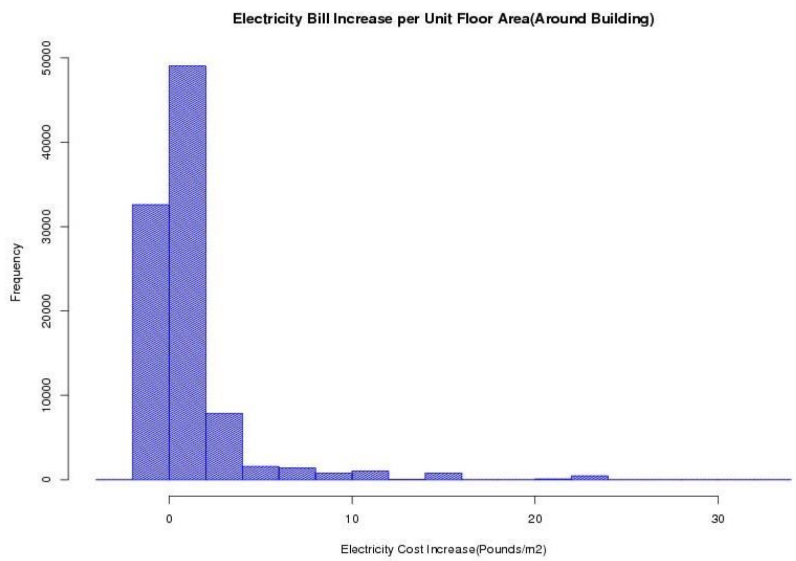



Figure 11  Electricity Cost Increase from Design to Operation under Scenario 2

## 5 Conclusions

Parametric analysis was carried out to assess the application of GSHP systems at city scale for a case study of Westminster, London. This analysis was specific to the influence of annual, monthly and hourly variation in heating/cooling demand estimation on the ratio of capacity to demand (C/D ratio) distribution map, and also the influence of COP difference between design and operation on the electricity consumption. The heating and cooling demands with annual, monthly and hourly variations for all the buildings in Westminster were firstly calculated and estimated. For the COP values, the sets of monitored data were collected from the metering equipment from all parts of the UK to produce a frequency distribution. According to this distribution, COPs were randomly assigned to each system as the actual operation values for all the buildings in Westminster. All the prepared data was then put into the city-scale model to obtain the simulation results for parameter analysis.

Two scenarios were considered in this study, 'Boreholes under Buildings' as Scenario 1 and 'Boreholes around Buildings' as Scenario 2. The results from both of scenarios can show the conclusions as below. The influence of the variation in building load estimation is more significant under Scenario 1 than under Scenario 2. However, it is in common that, for both of the scenarios, the annual and monthly estimations give the similar results, and the hourly estimation comparatively leads to a lower capacity to demand (C/D) ratio. It is suggested to consider the capital cost, C/D ratio distribution and also the building load satisfactory together to produce a wise design choice. The influence of COP variation is greater in Scenario 2 than Scenario 1. However, for both of the scenarios, the electricity cost change from design to operation is mainly concentrated within the range from £-1to £2 and the largest portion is from £0 to £1. In the city-scale planning, this part can be a financial concern on the risk management. Therefore, a comprehensive analysis including the capital cost, C/D ratio distribution, energy demand, and financial risk is recommended for possible district-level planning of GSHP systems.

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