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GSHP Application for Heating and Cooling at 'City Scale' for the City of Westminster

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ABSTRACT

Shallow geothermal energy is a clean and sustainable resource that can provide heating and cooling for buildings and infrastructure. Unlike deep geothermal energy, there is no location restriction for employing shallow geothermal energy, which means that it can be used everywhere in the world. The ground source heat pump (GSHP) system is a shallow geothermal technology to supply heating and cooling to buildings with geothermal energy underground. Many cities have a large amount of energy stored in the urban subsurface many times larger than their annual heating and cooling demands. Therefore, there is great potential for planning geothermal energy utilization at city scale, thus a low carbon city could be developed with reduced fossil fuel consumption and associated carbon emissions. In this study, a simulation model was develop based on GIS to identify how many GSHPs could be installed at the city scale without overusing the geothermal thermal energy underground and to estimate the contribution of such a system to the heating and cooling demands of the buildings. The model was built by embedding a PYTHON-based GSHP design code into ArcGIS software and was performed on the City of Westminster, a district in London (UK), to provide both heating and cooling as a case study under the following two scenarios; (a) boreholes are 'under buildings' and (b) boreholes are 'around buildings'. Under both scenarios, borehole allocation maps and ratio of capacity to demand maps were constructed. In addition, an analysis was performed to show the influence of achieving thermal balance on the electricity use and the ratio of capacity to demand distribution. The results demonstrate that (i) a great percentage of the buildings of Westminster can satisfy their own heating and cooling demand by installing GSHPs; and (ii)Achieving thermal balance could increase the electricity use, but has nearly no influence on the ratio of capacity to demand distribution of Westminster.

1. INTRODUCTION AND BACKGROUND

At the present, a large amount of energy is consumed to keep the living and working space at comfortable temperature. In the United Kingdom, space heating accounts for about 66% of the domestic energy bills (DECC, 2013) and delivers approximate 74% of the carbon dioxide emissions as the majority of heat related activities are from fossil fuel consumption in the domestic sector (DECC, 2012). Since the fossil fuel sources are limited and the energy demand for thermal comfort tends to rise, planning a large scale applicant of renewable energy is an effective solution to control CO2 emissions and secure energy consumption in a sustainable development way. In this respect, geothermal energy is a promising choice contributing to reducing dependency on fossil fuel because of the huge geothermal storage capacity worldwide. Many countries encourage the development of geothermal energy technologies to meet their renewable energy targets (Haehnlein et al., 2010).

Ground source heat pumps (GSHPs) is a typical shallow geothermal system of pumping heat from or to the ground to supply low carbon heating or cooling to buildings. Shallow systems require no specific geological condition or high temperature gradient, so they are increasingly popular worldwide as an environmental friendly alternative to traditional technologies such as gas fired boilers (Haehnlein et al., 2010). GSHPs can be mainly grouped into two types, closed loops and open loops. In closed GSHP, borehole system achieves heat exchange through the circulation of fluid in a closed U-loop embedded within an infill medium. In contrast, open loop GSHP systems utilize the heat convection mechanism of groundwater flow by extracting heated or cooled water. According to the UK Environment Agency (2009), the total number of installed GSHP systems in the UK at the time of year 2009 was 8000, of which, there were only 300 open loops (3.75%) and the rest are closed loops (96.75%). The main reasons for this situation is that, there is a risk that an open loop system will fail to extract the target water yield, whereas the risk of system underperformance in a closed loop GSHP system can be almost controlled by installation and operation. Closed GSHP systems can be classified as horizontal GSHP and vertical GSHP. Vertical GSHPs are normally constructed by placing two small-diameter polyethylene tubes in a vertical borehole, which horizontal GSHPs are placed in narrow trenches and this design requires great amount of ground area.

Although GSHP has been available for long time, applicants are generally limited to the small scale. If such ground source energy systems are employed to provide low carbon heating solutions to buildings and infrastructures at the city scale, a low carbon city would be developed. However, to achieve this, additional research work needs to be made with consideration of its feasibility in design and operation at the city scale. There has only a very few works on determination of potential capacity and sustainability of shallow geothermal energy on the large scale. Balke et al. (1977) quantified the recoverable heat per unit surface in Cologne, and Allen et al. (2003) estimated that providing space heating with hydro-geothermal source has the potential to ease urban heat island effects. More recently Herbert et al. (2013) provided a modelling method to estimate the ground source energy potential in urban aquifers.

In this paper, a GIS based simulation tool was developed to quantify how many GSHPs could be installed at the city scale without overusing ground thermal capacity, and to identify its contribution to both heating and cooling demands of buildings and infrastructures. This simulation tool is performed and discussed based on the case study of the City of Westminster, one district in London, UK. In addition, due to the current GSHP market distribution and urban land use limitations, the modelling and analysis in this paper are based on vertical closed loop GSHP systems only, which are currently most common-used for urban areas in the UK. The vertical GSHPs are considered to be suitable for large scale planning because they need relatively small plots of space; contact with the soil that varies little in temperature and thermal properties; consume the smallest amount of pipe and pumping energy; and can yield the most efficient performance (Kavanaugh and Rafferty 1997). However, if for a certain city, the resource is suitable for planning other types of GSHP systems, the simulation model is able to do the analysis according to the specific situation.

2. GSHP APPLICATION SIMULATOR FOR CITIES

2.1 Geothermal Potential

The theoretical geothermal potential of a specific area can be calculated using the following standard equation.

$$Q = Q_w + Q_s = V(nC_w + (1-n)C_s)\Delta T \tag{1}$$

where Q is the total theoretical heat potential content (kJ), Qw and Qs are the heat content stored in ground water and solid (soil) respectively (kJ), V is the volume of the ground (m3), n is the porosity, Cw and Cs are the volumetric heat capacities of water and solid in kJ/(m3K) respectively, and T is the temperature change of the whole ground in Kelvin.

This equation can give an estimate of geothermal energy potential available of a certain area based on a ground volume and related geological parameters. As a preliminary step of simulation, the calculated estimate is compared with the heating/cooling demand of this area. Thus, a rough heating/cooling capacity value, which is the ratio of geothermal energy potential to the heating/cooling demand, can be obtained to show the capability of geothermal energy to meet the local heating/cooling demand.

2.2 Simulation of GSHP Application for Heating and Cooling at city scale

If the estimate of geothermal potential is satisfied compared with heating and cooling demands, actual planning of GSHP systems within urban areas can heavily depend on availability of land area. In addition, it is well known that correctly sizing the ground heat exchangers according to energy demand is significantly important for vertical GSHP system design (Shonder and Hughes, 1998). In order to estimate how many GSHPs can be installed in specific areas of cities or districts, and how many are required to satisfy heating demands, it is necessary to find an authorized method to do the ground heat exchanger (GHE) design calculations. With integration with land use datasets, heating/cooling demands of buildings and ground properties, a simulation tool can be developed to quantify the exact geothermal capacity of specific areas.

Most current GHE design software packages employ the Cylinder and Line Source Method, which has been considered to be the most accurate model through comparisons with calibrated data from actual installations (Shonder and Hughes, 1998). A PYTHON code based on this method was developed to size combined heating and cooling GSHP with the given energy demands of a building. This code was embedded into ArcGIS software, which is a widely used platform for spatial design and analysis. The PYTHON code developed for this study is based on the following equations to determine the required vertical borehole length Lh for heating;

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

and Lc for cooling(Kavanaugh and Rafferty, 1997).

$$L_c = \frac{q_a R_{ga} + (q_{lc} - \overline{W}_c)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p} \tag{3}$$

where Fsc is the short-circuit heat loss factor, PLFm is the part-load factor during design month, qa is the net annual average heat transfer to the ground (W), qlh is the building design heating block load (W), qlc is the building design cooling block load (W), Rga is the effective thermal resistance of the ground in annual pulse (mK/W), Rgd is the effective thermal resistance of the ground in daily pulse (mK/W), Rgm is the effective thermal resistance of the ground in monthly pulse (mK/W), Rb is the thermal resistance of borehole (mK/W), tg is the undisturbed ground temperature (K), tp is the temperature penalty for interference of adjacent boreholes (K), twi is the liquid temperature at heat pump inlet (K), two is the liquid temperature at heat pump outlet (K), Wh is the power input at design heating load (W), and Wc is the power input at design cooling load (W).

These equations represent the variable heat rates of a ground heat exchanger with consideration of three different heat pulses (Kavanaugh and Rafferty, 1997). Equations (2) and (3) require five site specific or spatial parameters as inputs: heating demand per building, cooling demand per building, thermal conductivity, thermal diffusivity, and ground temperature. Heating and cooling demands can be obtained from electricity bills or can be calculated according to the empirical energy benchmarks based on building characteristics such as building type, building height and floor area. For a specific borehole system, the thermal conductivity and the thermal diffusivity are estimated by doing TRT test at the site. However, for the large scale, it is impossible to obtain thermal properties in this way. Since the thermal properties depend on the nature of the soil, typical thermal property look-up tables can be used for approximately estimating the thermal conductivity and the thermal diffusivity based on the geological condition. Ground temperature is another important site data in the design. Although the soil temperature varies with daily and seasonal cycles, at depth of about 15m, the temperature is approximately constant and equal to the mean annual air temperature (Rybach and Sanner, 2000). Below this depth, the temperature increases with depth at a rate depending on the geothermal gradient. The geothermal gradients can vary from location to location, and many studies have investigated and given the local thermal gradients for different regions (BGS, 2011). These values must then be prepared in a format compatible with ArcGIS. Sizing Heat pump is a key intermediate step in the GHE design calculation. A series of heat pumps with capacity range from 5 to 75 kW are therefore also included within the model. If the required capacity is greater than this range, a combination of two or more heat pumps is applied. In the calculation, the temperature penalty tp is used as a parameter to consider the influence of thermal interference of adjacent boreholes. Thus, the temperature decreases surrounding the borehole, and the temperature reduction drops with time. Therefore, it can be assumed that no heat is diffused out of a square cylinder with sides equal to the borehole separation distance (Kavanaugh and Rafferty, 1997).

The PYTHON code gives the output of the total required borehole length of GHE per building, which is the larger one of the results from Equations (2) and (3). The individual borehole length is set to be 150m, which is the common-used value in practice for vertical closed loop GSHP installations in the UK. The number of boreholes per building is then calculated based on the total and the individual length values.

The land area may be a restriction to install the required number of boreholes for some buildings. In such cases, the model can inversely calculate the maximum heating and cooling demands with the maximum possible borehole length (the maximum borehole number × 150m) for a land area. In this study, the ratio of capacity to demand (C/D) is defined to represent, the GSHP capacity of a building, and calculated by dividing the maximum possible number of boreholes within the building's land area by the required borehole number. If the C/D ratio of a building is equal to or greater than 100%, both heating and cooling demands of this building could be fully supplied by its own GSHP system.

3. RESULTS AND DISCUSSION OF CASE STUDY OF WESTMINSTER

3.1 Data Preparation of Westminster

According to Section 2.2, the site specific or spatial inputs in the design calculation were firstly prepared for the case study, which were heating demand per building, cooling demand per building, thermal conductivity, thermal diffusivity, and ground temperature.

For the calculation of heating and cooling demands, UKMap, a GIS database, was used to collect spatial information about buildings in Westminster including building type, floor area and height. According to this database, there are 95,817 buildings within this district. 83% of the floor area is for residences, retails, and offices. The rest are for hotels, schools, hospitals and leisure facilities (Choudhary, 2012). The unit value of heating/cooling demand per building type (in KWh m-2 year-1) was looked up from (a) DECC certificates, which were compiled and released by the UK Centre for Sustainable Energy, (b) UK CIBSE Guide F and CIBSETM46, and (c) the 2011 Energy Distribution Charts (EDC). The design heating/cooling block load per building (qlh in kW) was calculated first by multiplying the heating/cooling demand per building type in KWh m-2 year-1 with the floor area of a building, and then dividing by total heating/cooling hours per year (2,160 hours in this study, assuming 12 hours of heating per day for an half year and 12 hours of cooling per day for the other half year).

The thermal conductivity and thermal diffusivity maps were developed 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. For each type of soil, its thermal property assignments refer to the logs from site investigation work by BGS. By this way, a thermal conductivity map and a thermal diffusivity map were developed with grids of size 50m×50m in east-west and north-south directions and 1m in the vertical direction. In the case study, the average thermal conductivity and the average thermal diffusivity within the depth of 150m of each grid was used to develop the thermal conductivity and the thermal diffusivity maps of the whole area.

For the ground temperature, as there was no study specifically introducing the values of Westminster, the ground temperature of London was used instead in the design. Headon et al. (2009) gave the underground temperature information of London city based on the well data as 12.3°C at 60m depth, 12.8°C at 80m depth and 13.1°C at 100m depth. Accordingly, the ground temperature in the design was set to be 12.8°C, which was considered as the average ground temperature value within the depth of 150m.

3.2 Geothermal Potential of Westminster

After preparing the required data, a calculation based on Equation (1) was processed to roughly estimate the geothermal potential beneath the city of Westminster and also the ratio of geothermal potential to the demand. The results are illustrated in Table 1.

Table 1 Geothermal Potential Estimation of Westminster

	Min	Max
Thickness (m)	150	150
Area(km^2)	21.48	21.48
Volume of urban ground(m^3)	3.22×10^9	3.22×10^9
Porosity	0.05[a]	0.2[a]
Volume of water (m^3)	1.61×10^8	6.44×10^8
Heat content in water(kJ K^{-1})	6.74×10^{11}	2.70×10^{12}
Volume of solid (m^3)	3.06×10^9	2.58×10^9
Heat content in solid(kJ K^{-1})	2.45×10^{12}	2.06×10^{12}
Temperature change (K)	4	6
Potential heat content (kJ)	1.25×10^{13}	2.86×10^{13}

Potential heat content per km^2 (kJ km^{-2})	5.81×10^{11}	1.32×10^{12}
Average heating demand(kJ km^{-2} year^{-1})	3.91×10^{11}	
Capacity for heating	1.49	3.38
Average Cooling demand(kJ km^{-2} year^{-1})	2.68×10^{11}	
Capacity for cooling	2.17	4.93

[a]Zhu *et al* (2010)

In Table 1, the theoretical geothermal potential per square kilometre of Westminster was quantified within 150m of the ground-surface. The heating and cooling capacities were estimated by dividing the geothermal heating/cooling potential by the total heating/cooling demand. The depth was set referring to the current practical borehole length of systems installed in the UK. The geological condition was set referring to the data of London given by Zhu et al. (2010).The temperature change was set to be both 6 °C and 4 °C. The upper value is the minimum temperature recommended in legal regulations of several countries (Haehnlein et al., 2010), and the lower value is the commonly used temperature reduction of ground due to heat extraction (Kavanaugh and Rafferty 1997).

The average total heating and cooling demands were estimated by dividing the total heating/cooling consumption of all the buildings within Westminster per year by the land area. It can be seen that the geothermal potential is greater than both annual heating and cooling demands. According to the results, the cooling value is smaller than the heating one, because currently in the UK, cooling is mainly applied in large and intensively occupied commercial and public sector buildings due to high internal heat gains from occupants and electrical equipment. However, as the climate is getting warmer, the cooling requirement is increasingly important for both domestic and commercial buildings (Arthur et al., 2010). Therefore, it is worthwhile considering both heating and cooling demand for GSHP system design at city scale, which can also benefit temperature balance of ground in the long term.

3.3 Verification of Borehole Design Code

The developed design code was verified by comparison with MIS (DECC, 2008) and GLD commercial software (Gaia Geothermal) because they are based on the same calculation methods. In order to compare the results of these three models, Full Load Equivalent Run Hours (FLEQ) was set to be 1800, according to the heating consumption of a typical residential building in the UK. In the analysis, the heating time was set to be 12 hours per day for half the year, which is 1825 FLEQ Hours in total approximately equal to 1800. The running time of GSHP was set to be 30 years and the borehole property values were selected according to MIS.

A calculation of the maximum power extracted per unit length of borehole against ground temperature is shown in Figure1. The results from three methods at a given temperature are quite close to each other. As the thermal resistance of the ground used in the PYTHON code and MIS are set according to the conditions at 12 °C ground temperature, the slopes of the curves from the PYTHON code and the MIS model are different from the slope generated by the GLD software. The results obtained from the PYTHON code were slightly lower than the ones from MIS because the FLEQ used in the MIS look-up tables (1800), was smaller than the value used in the PYTHON design (1825).

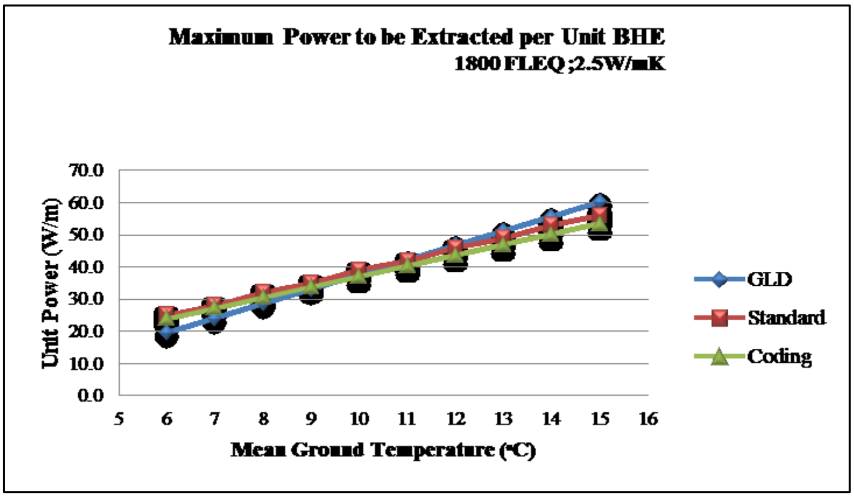

Figure 1 Comparison of code, GLD and MIS in maximum power extracted per unit BHE Length

3.4 GSHP system for Heating and Cooling for Westminster

As the estimate of geothermal potential of Westminster is encouraging (Table 1), availability of land area becomes an important restriction for urban areas. In this case study, the required number of boreholes for each building was allocated at a spatial position. 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. In order to avoid thermal interference, the spacing between any two boreholes was fixed at 6 metres, as per the MIS (DECC, 2008). This means that outside this square cylinder, the ground temperature is assumed to be undisturbed. All the consumptions used in the design are demonstrated in Table 2.

Table 2 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
Heating Hours per Day	hours	12	Chosen Design value
Heating Days per Month	days	30	Chosen Design value
Heating Months per Year	months	6	Chosen Design value
Cooling Hours per Day	hours	12	Chosen Design value
Cooling Days per Month	days	30	Chosen Design value
Cooling Months per Year	months	6	Chosen Design value
Design Operation Time	years	30	Chosen Design value
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)

Scenario 1 is more suitable for new and refurbished buildings, but scenario 2 is more practical for existing buildings and can be achieved by using directional drilling at a shallow depth to the target borehole location and then by drilling vertically downwards. In these two cases, the difference in the allowed areas for locating the boreholes can lead to the difference in the maximum number of boreholes. Figure 2 shows the borehole allocation map of a small section for Scenario 1 and Figure 3 shows the map of the same location for Scenario 2. The shaped polygons and the points stand for the buildings and the installed boreholes, respectively. The spacing between any two boreholes is fixed at 6 metres. In scenario 2, boreholes are installed in a buffer area that is within 3 meters of the edges of a building, both away from and under it. The installation area can be changed in the model to correspond to more restrictions, such as pavements and parking areas.

Figure 2 Borehole allocation map of a corner in Westminster (Scenario 1 'Under Buildings')

Figure 3 Borehole allocation map of a corner in Westminster (Scenario 2 'Around Buildings')

For both scenarios, the C/D ratios were calculated for all the buildings in Westminster. Figure 4 shows the map of the C/D ratio for Scenario 1, and Figure 5 shows the map for Scenario 2. Green color represents the buildings can have enough capacity to support their own heating and cooling demands. Red represents buildings that can support less than 50% heating demand due to their small land area. The rest buildings with ratio in the range of 50%-100% are indicated by the yellow color. In Scenario 1, 51% of buildings can meet their own heating and cooling requirements. Such buildings are generally found at the edges of built-up areas. In Scenario 2, 67% of the buildings can have a GSHP system with capacity larger than their heating and cooling demands. The main reason that such a high percentage of buildings can satisfy their own demands is that, for the total 95,817 buildings in Westminster, 77,355 buildings have 5 floors or fewer (80.7%), 17,638 buildings have 6-10 floors (18.4%) and only 824 buildings have more than 10 floors (0.87%). the typical heating demand for these buildings is only around 40W/m^2,so it can be inferred that Most of the low rise (5 floors or fewer) buildings can meet their own heating demands by GSHP. The difference between the two scenarios is mainly because there are quite many long, narrow buildings in Westminster. For these buildings, more installation area is available for boreholes in Scenario 2 than Scenario 1. By comparison, buildings in the central area can have more boreholes installed under the buildings due to the different building shape.

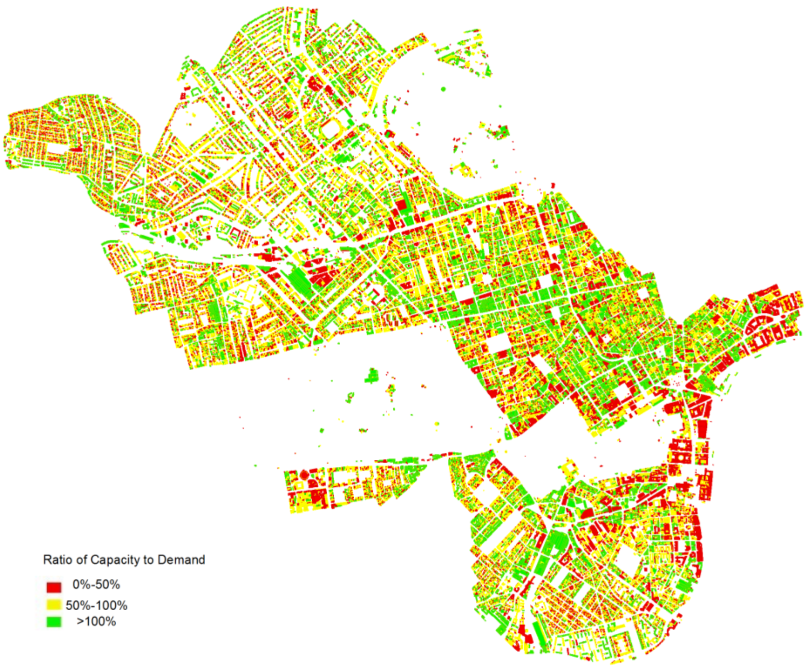

Figure 4 Map of Ratio of Capacity to Demand of Westminster for Heating and Cooling (Under Buildings)

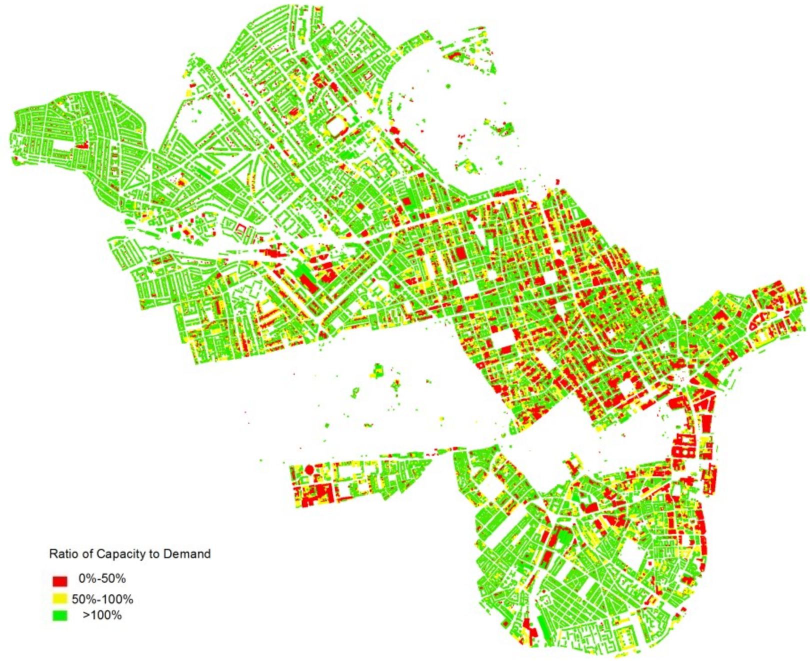

Figure 5 Map of Ratio of Capacity to Demand of Westminster for Heating and Cooling (Around Buildings)

If only the heating is considered in the design, the ratio distributions are slightly different from the cases including both heating and cooling. In Scenario 1 and Scenario 2, 70% (Figure 6) and 81% (Figure 7) of buildings have capacity to meet their heating demands only, which are 20% and 14% higher than considering both heating and cooling together, respectively. The reason is that the borehole length is determined to be the larger one between the two lengths resulting from heating and cooling. In Westminster, 98% of the buildings have only heating demands and 48% have both heating and cooling demands. In this percentage of 48%, 34% of buildings have more heating demands than cooling, and the rest 14% have the opposite situation. Therefore, for these 14% of buildings, the required borehole length is larger for heating and cooling together than heating only, thus, the percentage of green color is reduced accordingly. Although the percentage of buildings in green color decreases, the temperature is more balanced underground due to the heat replenishment by providing cooling demands.

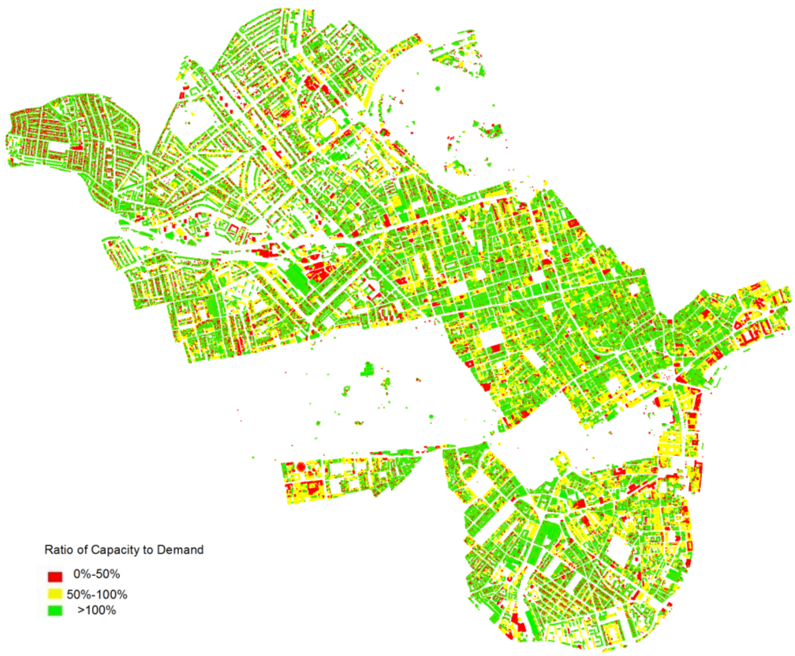

Figure 6 Map of Ratio of Capacity to Demand of Westminster for Heating only (Under Buildings)

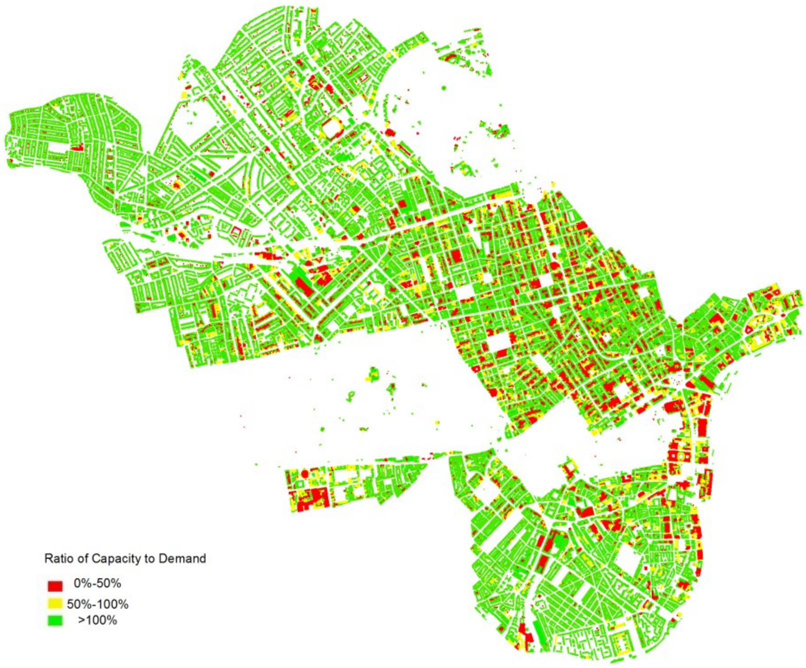

Figure 7 Map of Ratio of Capacity to Demand of Westminster for Heating only (Around Buildings)

3.5 Thermal Balance for Westminster

Providing heating and cooling together by GSHP system can improve the temperature compensation underground, but there still exists unbalance due to the difference between the heating and the cooling supplies. The only way to achieve the absolute balance is to make net heat transfer between the GSHP system and the ground to be zero. This means the lower value of the heating and the cooling demands of each building needs to be increased to meet this condition. In such case, the electricity utilization and the borehole length of each building will change to some extent.

For each building, the heat transfer values due to the heating and the cooling were calculated based on COP and EER, respectively. The lower rate between these two values was increased to be equal to the higher one. Following this, a new heating or cooling demand was obtained for redesign of the GSHP system. Figure 8 illustrates the distribution of electricity utilization growths of all the buildings in Westminster for thermal balance. It can be seen that almost all the buildings have the electricity increase within the range of 0-30kWh/m^2. However, the change for thermal balance has nearly no influence on C/D ratio distribution for both scenarios (Figure 9).

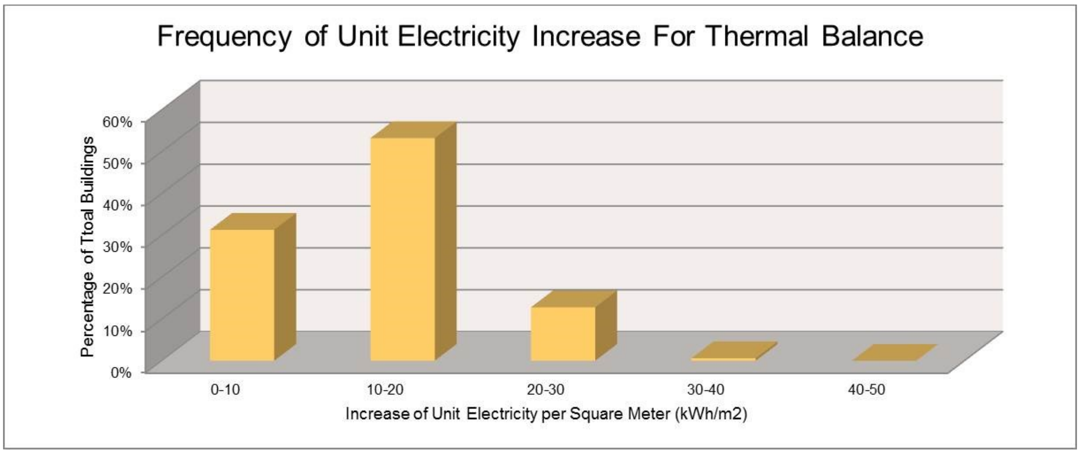

Figure 8 Frequency of Unit Electricity Increase for Thermal Balance of Westminster

4. CONCLUSIONS

Vertical closed loop GSHP system can be an environmental friendly application for supplying heating and cooling in the urban areas. In this paper, a city-scale simulation tool was developed to identify how many GSHPs could be installed in a district without overusing geothermal energy and to calculate the ratio of its contribution to the heating and cooling demands of buildings. A PYTHON based GSHP design code was developed and embedded in ArcGIS software in order to integrate building scale design of system into city scale analysis. The fidelity of the building-scale design code was verified by comparing the results with outputs from MIS standards and from the commercial GLD software. The City of Westminster was selected as a case study. Two scenarios for borehole installations ('under buildings' and 'around buildings') were examined and the borehole allocation maps and C/D ratio distribution maps were generated. Results demonstrate that a large proportion of buildings (51% for Scenario 1 and 67% for Scenario 2) can install enough boreholes to satisfy their own heating and cooling demands, which are 20% and 14% lower than considering heating only in the design, respectively. To achieve thermal balance of underground in Westminster, nearly all the buildings need to increase electricity use of 0-30kWh/m^2 to make net heat transfer rate to be zero, but there is no influence on the C/D ratio distribution.

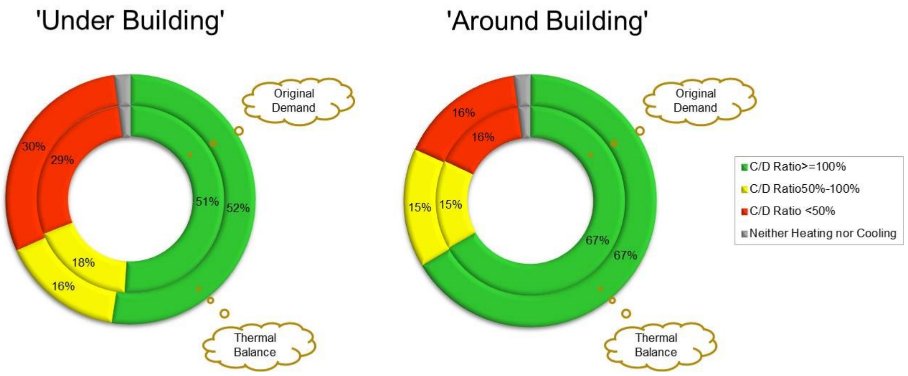

Figure 9 Influence of Thermal Balance on C/D Ratio Distribution of Westminster

5. ACKNOWLEDGEMENT

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