Benefits and Optimisation of District Hybrid Ground Source Heat Pump Systems

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ABSTRACT: Buildings consume large amounts of energy, largely to satisfy their heating and cooling needs. Since most of this energy is derived from fossil fuels, buildings are responsible for a significant share of the world's CO_2 emissions. Shallow geothermal energy is a promising sustainable source of energy which can potentially satisfy the thermal requirements of buildings not only economically but also with reduced carbon emissions. For high density urban areas, buildings can be connected to district hybrid ground source heat pump (HGSHP) systems for heating and cooling purposes. This study discusses the benefits of district over individual HGSHP systems. A methodology for the optimisation of district HGSHP systems is proposed which considers building thermal demand regimes. Such optimisation can reduce the total lifetime costs of heating and cooling, capital investments and payback periods of HGSHP systems. The importance of considering the demand regimes in the optimisation is demonstrated through a case study. The case study shows that an optimised district HGSHP system can have significant financial benefits over individual HGSHP systems and therefore make district systems more attractive to investors.

1 INTRODUCTION

Currently, buildings consume large amounts of fossil fuels for heating and cooling purposes to make them significant CO_2 emitters. To reduce emissions, low-carbon geothermal energy from shallow depths can be supplied to buildings to satisfy their thermal needs. The capital costs of shallow geothermal energy installations, or ground source heat pump (GSHP) systems, can be high in comparison to traditional heating and cooling systems. Some governments, for example the UK, have introduced incentives to compensate high installation costs of these systems. More research into optimisation of GSHP system is needed to increase their financial attractiveness to potential investors.

Previous research into the economics of geothermal systems suggests that hybrids of GSHP and traditional heating and cooling systems (HGSHP systems) can often be more financially beneficial heating and/or cooling options than GSHP only systems (for example, Hackel et al. (2009), Alavy et al. (2013), Nguyen et al. (2014) and Hénault et al. (2015)). In such systems, the GSHPs are sized for a certain portion (or shave factor) of a peak thermal demand α (Alavy et al., 2013). As such, GSHPs provide baseline thermal power up to their installed capacities and the rest is topped-up by a traditional system, for example, a gas boiler in heating or a cooling tower in cooling. This arrangement allows the expensive ground heat exchangers (GHEs) to provide most of the thermal energy (usually 70 – 95 % of the annual required energy) while the comparatively cheaper traditional systems to provide the balance of the energy.

In highly populated urban areas, buildings are located close to each other, so they can be combined into districts for thermal energy supply purposes. In such cases, the energy would be provided by centralised district systems. Just as occurs with individual HGSHP systems, district HGSHP systems could be more economical when sized to a certain shave factor α. In the design and optimisation of district HGSHP systems, the specific variations of thermal power demand, particularly in time, of different types of buildings needs to be taken into account.

This study evaluates likely financial benefits of district over individual HGSHP systems. In particular, the study proposes a methodology to consider thermal demand regimes of individual buildings in the design of district HGSHP systems, so that such systems can be optimised. An example case demonstrates the proposed methodology and the potential advantages of district HGSHP system arrangements.

2 METHODOLOGY

2.1. Building occupancy regimes

Building occupancy is a major factor influencing buildings' thermal demand regimes or the periods when buildings need thermal power. When buildings are unoccupied, their heating or cooling systems are usually switched off or on set-back mode. When buildings are occupied, their heating or cooling systems are usually switched on and may supply thermal energy to the buildings depending on the current ambient air temperature and other factors (eg. internal gains). Different buildings tend to be occupied at different rates at any given time, albeit there are similarities depending on nature of activities in buildings. For example, residential buildings are likely to be less occupied during daytime and predominantly occupied during nights, whereas commercial buildings are likely to be occupied during office hours and unoccupied for the rest of the time.

In this study, two building types were distinguished: a residential building (Type A) and an office building (Type B). The occupancy of a building at a particular point of time is modelled by its probability of presence *P(p)*. The probability of presence is the probability of the building being occupied at a particular point of time. The assumed *P(p)*'s of the two building types at two distinct time periods (9 am – 6 pm and 6 pm – 9 am) are shown in Table 1. This is a simplified representation of possible and more complex building occupancy regimes as the purpose here is to illustrate the principles of the proposed HGSHP optimisation methodology.

Table 1. Occupancy and thermal demand of the two building types for the example problem.

	Probability of presence *P(p)*		Design heating demand HD_{design}, kW	Annual heating energy E_j, kWh
	9 am – 6 pm	6 pm – 9 am		
Type A (Residential)	0.5	0.9	10	37,890
Type B (Office)	0.9	0.1	10	15,340

2.2. Building thermal demands considering occupancy regimes

The example case was performed for the climatic conditions of London, UK. In this climate, even if cooling is provided to a building, the annual building heating demand tends to be higher than its annual cooling demand. Thus, HGSHP systems are generally sized for heating with GHEs sized for a reduced yearly average ground load (Section 2.3). The HGSHP design methodology is very similar for both heating only and heating dominant cases, so the impact of thermal demand regimes on sizing of HGSHP systems would be the same in these cases. To demonstrate general principles of the proposed optimisation methodology, the buildings are assumed to require heating only.

Building heating demand amounts and regimes were assumed to depend on ambient air temperatures and occupancy of buildings. Other factors, such as fractions of heating use and internal temperature set points, can also affect building thermal demands and should be taken into account in detailed analyses. However, to keep the demonstration simple, these additional parameters are not considered.

The building heating demands are assumed to be proportional to ambient air temperatures with an assumed baseline ambient air temperature for heating of t_{base} = 16 °C. The baseline temperature determines when heating is needed: if an ambient air temperature is less than the baseline temperature, a building needs heating. The peak heating power demand HD_{max} occurs at the minimum ambient air temperature t_{amb_min}. In the analysis, both Type A and B buildings were assumed to have the same heating power demands $HD_{design,A} = HD_{design,B}$ = 10 kW at the average ambient air temperature of the heating design month in London, t_{design} = 4.4 °C (Table 1). The heating demand of the building k at any particular hourly timestep i, when the ambient air temperature is $t_{amb,i}$, is calculated as

$$HD_{k,i} = \frac{(t_{base} - t_{amb,i})}{t_{base} - t_{design}} HD_{design,k} \quad (1)$$

If occupied, a building is assumed to require 100% of heating power estimated for a particular ambient air temperature. If unoccupied, the building is assumed to have a zero power demand. Since, overall, Type A buildings have a greater occupancy than Type B buildings, Type A buildings require more heating energy annually than Type B buildings, all other factors being equal (Table 1).

The annual building heating energy is calculated as the sum of the energy required by the building at each hourly timestep i of a year j. Considering $P(p)_{k,i}$ of the building k at the hourly timestep i, the annual heating energy of the building, $E_{k,j}$, is

$$E_{k,j} = \sum_{i=1}^{8760} HD_{k,i} P(p)_{k,i} \quad (2)$$

The lifetime heating energy required for the building k can be estimated as

$$E_{k,tot} = T_{life} E_{k,j}, \quad (3)$$

where T_{life} is the life time of the HGSHP system.

Similarly, if two building A and B are considered, their annual heating energy at year j, $E_{A+B,j}$, and lifetime heating energy, $E_{A+B,tot}$, are

$$E_{A+B,j} = \sum_{i=1}^{8760}(HD_{A,i}P(p)_{A,i} + HD_{B,i}P(p)_{B,i}) \quad (4)$$

$$E_{A+B,tot} = T_{life}E_{A+B,j} \quad (5)$$

2.3. Sizing GHEs

In this study, the ASHRAE design approach is used to size GHEs (Philippe et al., 2010). According to this method, the design length of GHEs is

$$L_{GHE} = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_h R_{6h}}{T_m - (T_g + T_p)} \quad (6)$$

The descriptions of the parameters in Equation 6 are given in Table 2.

Table 2. GHE design parameters.

Design parameter	Value	Description
q_h, kW	Calculated based on assumed building thermal demands, *P(p)*s, α and COP_{GSHP}	Peak hourly ground load
q_m, kW		Monthly ground load
q_y, kW		Yearly average ground load
R_b, m · K/W	0.111	Effective thermal resistance of the borehole
R_{10y}, m · K/W	0.212	Effective thermal resistance of the ground to 10 years ground load
R_{1m}, m · K/W	0.197	Effective thermal resistance of the ground to one month ground load
R_{6h}, m · K/W	0.113	Effective thermal resistance of the ground to 6 hours ground load
T_m, °C	2.3	Mean GHE fluid temperature
T_g, °C	13.0	Undisturbed ground temperature
T_p, °C	0	Temperature penalty

The GHE ground thermal load design parameters (q_y, q_m and q_h) were calculated based on the estimated building thermal demands, their *P(p)*'s, the shave factor of a particular HGSHP configuration α and the coefficient of performance of GSHPs COP_{GSHP}. The rest of the parameters are defined by the ground thermal properties and GHE configurations. For the example case, these parameters are set following the typical values used for vertical borehole GHEs in London and assumed to be the same for all system configurations of the example case (Table 2). The GHEs are assumed to be installed sufficiently apart from each other to not thermally interact (hence, T_p = 0). For a more detailed explanation of the GHE calculation method, Philippe et al. (2010) should be consulted.

2.4. Financial indicators

Financial comparisons of different heating system arrangements and configurations were performed based on (a) *total normalised costs of heating* over lifetimes of heating systems and (b) *payback periods*. The *total normalised costs of heating* were calculated considering the capital costs of HGSHP systems and the lifetime costs of the heating energy delivered to the building in net present values. The costs of heating systems inside buildings (for example, in-room heating units, internal distribution pipework) and HGSHP maintenance costs were assumed to be the same for all HGSHP configurations and, hence, are not included into the comparisons. The unit costs and other parameters for the financial comparisons are summarised in Table 3.

Table 3. Financial comparison assumptions.

Parameter	Value
Installation cost of 1 kW of GSHPs, ic_{GSHP}, £	240
Installation cost of 1 kW of gas boiler, ic_{boil}, £	25
Installation cost of 1 m of GHEs, ic_{GHE}, £	37.5
1 kWh from electricity, c_e, £	0.17
1 kWh from gas, c_g, £	0.05
COP of GSHPs, COP_{GSHP}	3.5
COP of gas boiler, COP_{boil}	0.95
Life time of HGSHP system T_{life}, years	20
Discount rate, *DR*	0.05
Government incentive rate per 1 kWh of geothermal heat, r_{RHI}, £	0.0884

The capital cost of the particular configuration of a HGSHP system, where the GSHP is sized to a particular α, is calculated as

$$C_{cap} = C_{GSHP} + C_{GHE} + C_{boil} \quad (7)$$

where C_{GSHP} is the capital cost of the ground source heat pump; C_{GHE} is the capital cost of the GHEs and C_{boil} is the capital cost of the boiler. These costs are calculated as

$$C_{GSHP} = \alpha HD_{max} ic_{GSHP} \quad (8)$$

$$C_{GHE} = L_{GHE} ic_{GHE} \quad (9)$$

$$C_{boil} = (1-\alpha) HD_{max} ic_{boil} \quad (10)$$

Note that the capital costs of the HGSHP system sized to the same α will be different for buildings A and B as the lengths (and therefore the costs) of GHEs for these buildings are different (see Equation 9).

In the calculations of annual heating energy costs, the UK government's renewable heat incentive (Ofgem, 2016) is taken into account. The incentive compensates high capital investments into GSHP systems and is paid on a prorata basis for each kWh of geothermal energy delivered. The incentives were calculated as for non-domestic (commercial) installations at the $r_{RHI} = 0.0884$ £/kWh rate paid over the first 20 years of GSHP installation. The annual cost of heating energy at any particular year j, including the renewable heat incentive, is calculated as

$$C_{h,j} = C_{h\_GSHP,j} + C_{h\_boil,j} - RHI_j \quad (11)$$

where $C_{h\_GSHP,j}$ is the cost of heating energy provided by the GSHPs at the year j; $C_{h\_boil,j}$ is the cost of heating energy provided by the boiler at the year j and RHI_j is the renewable heat incentives received at the year j.

The annual heating energy provided by GSHPs during year j, $E_{GSHP,j}$, is a share of the required annual building energy, E_j, and determined by the design shave factor, α. When needed, the boiler tops the heating energy supplied by GSHPs up to the required amount. The annual heating energy provided by the boiler during year j, $E_{boil,j}$, is

$$E_{boil,j} = E_j - E_{GSHP,j} \quad (12)$$

Considering the coefficients of performance of the equipment, the annual costs of the heating energy in Equation 11 are estimated as

$$C_{h_{GSHP},j} = \frac{E_{GSHP,j}}{\mathrm{COP}_{GSHP}} c_e \quad (13)$$

$$C_{h_{boil},j} = E_{boil,j}\mathrm{COP}_{boil} c_g \quad (14)$$

$$RHI_j = \frac{E_{GSHP,j}(1-\mathrm{COP}_{GSHP})}{\mathrm{COP}_{GSHP}} r_{RHI} \quad (15)$$

The annual costs of heating energy are converted into net present values to estimate the total lifetime cost of heating as

$$C_{tot} = C_{cap} + \sum_{j=0}^{T_{life}} \frac{C_{h,j}}{(1+DR)^j} \quad (16)$$

where the assumed discount rate DR. Note that the discount rate prediction is a complex process and should be performed for a particular project (see examples in Oxera (2011)). Here, for demonstration purposes, DR of 5% is assumed as a reasonable value for a low-carbon technology projects (Oxera, 2011). The Equation 16 follows Alavy et al. (2013).

Since heating systems with different total lifetime required heating energy will be evaluated, the total lifetime cost of heating C_{tot} is normalised by the amount of heating energy provided during the lifetime of the heating system, E_{tot}. Hence, all comparisons are performed on the basis of the total normalised costs of heating in £/MWh which is

$$TNC = \frac{C_{tot}}{E_{tot}} \quad (17)$$

The *payback period* of a particular HGSHP system configuration, *PBP*, is calculated by dividing initial capital investment by the total annual returns in energy savings as

$$PBP = \frac{C_{cap} - C_{boil\_\alpha=0}}{\sum_{j=0}^{T_{life}} \frac{C_{h,j} - C_{h\_\alpha=0,j}}{(1+DR)^j}} \quad (18)$$

In *PBP* calculations, the initial capital investments were taken as the difference in the capital costs of the HGSHP system, C_{cap} (Equation 7), and a gas-only heating system, $C_{boil\_\alpha=0}$ (hence, for a gas heating system, the payback period is zero). The annual returns are quantified as the difference between annual heating energy costs in cases of the HGSHP including renewable heat incentives, $C_{h,j}$ (Equation 11), and the gas-only heating systems, $C_{h\_\alpha=0,j}$, converted into net present values. The payback periods were calculated in years needed to return initial investments.

3 RESULTS

In the case study, individual and district arrangements of HGSHP systems for mixes of two buildings are compared. The following three mixes of Type A and B buildings are evaluated:

- "A+A" mix: a Type A + a Type A buildings
- "B+B" mix: a Type B + a Type B buildings
- "A+B" mix: a Type A + a Type B buildings

In the individual arrangements, the thermal demands per building are used to size the GHEs. In the district arrangements, the thermal demands of the two buildings are combined before sizing the GHE. Thus, for these two arrangements of a same mix, the q_y and q_m thermal loads might be different at the same q_h.

For both individual and district heating system arrangements, the GSHPs are sized for a range of α values from 0 to 100 % with a step of 3 % to cover possible configurations of the HGSHP systems. Financial indicators of the resultant configurations of HGSHP systems are calculated to determine their cost effectiveness.

The results of the financial comparisons for the three building mixes are presented in Figure 1. In the figure, total normalised costs of heating *TNC* in £/MWh (Equation 17) are plotted against capital costs of different heating system configurations, C_{cap} in £ (Equation 7). In each plot, C_{cap} along the horizontal axis varies from the cost of a gas-only (the most left point, $\alpha = 0$) to the cost of GSHP-only (the most right point, $\alpha = 100$ %) heating systems. The points in between represent the hybrid heating system configurations with α increasing from left to right. For each building mix, the minimum value of

TNC represents the most financially optimal solution. Key observations from Figure 1 are summarised in Table 4.

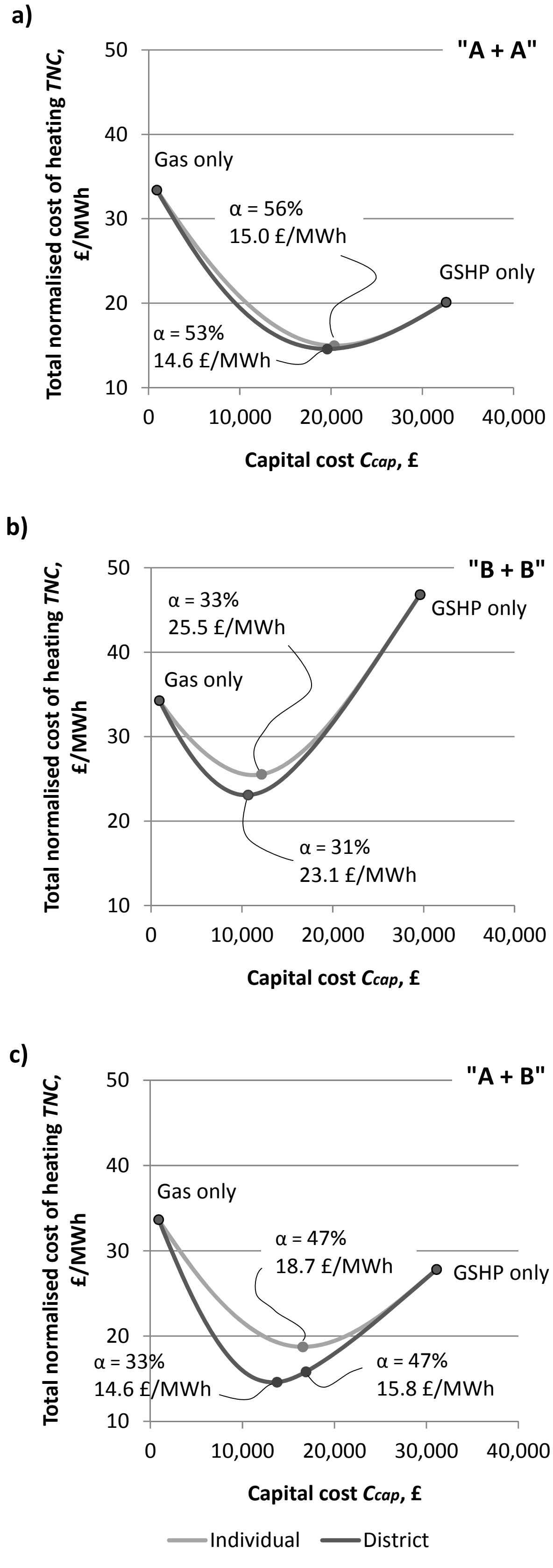

Figure 1. Total normalised costs of heating TNC for three building mixes: a) "A + A", b) "B + B" and c) "A + B".

Table 4. Financial comparison.

Building mix	Type of HGSHP system	At optimum configuration			
		α, %	*TNC*, £/MWh	Share of geothermal energy, %	C_{cap}, £
"A+A"	Individual	56	14.6	91.3	20,300
	District	53	15.0	91.1	19,600
"B+B"	Individual	33	25.5	75.5	11,300
	District	31	23.1	79.2	10,700
"A+B"	Individual	47	18.7	86.6	16,600
	District sized conventionally	47	15.8	96.1	16,900
	District	33	14.6	88.8	13,200

From Figure 1, if GSHP-only heating is compared with gas-only alternatives, a GSHP-only heating is more economical than a gas-only heating in the "A+A" and the "A+B" mix. However, in the "B+B" mix, a GSHP-only heating is a more expensive option compared to a gas-only heating. In addition, *TNC* for the gas-only options are the same for both "A+A" and "B+B" mixes while there is a significant difference in *TNC* between these two mixes for GSHP-only options. Such differences are explained by the principles of GHE sizing. The Type A and B buildings have the same design heating demands (Table 1) which largely determine the required lengths of "expensive" GHEs, and therefore influence the cost. At the same time, annually, less "free" geothermal energy is supplied to Type B buildings compared to Type A buildings due to the differences in their annual heating energy demands (Table 1). Hence, the high capital costs of the GSHP systems are not compensated by the delivered "free" geothermal energy in Type B buildings as much as they are in Type A buildings. In other words, "expensive" GHEs are utilized more efficiently in Type A buildings compared to Type B buildings.

In all three building mixes considered, the *TNC* is at a minimum when the hybrids of a GSHP and a boiler are used for the heating in comparison to the GSHP-only and gas-only systems. In Figure 1, the minimum points at the *TNC* curves represent the most financially optimum HGSHP configurations which correspond to the GSHPs sized to certain shares of peak power demand HD_{max} or shave factors α.

In the optimum cases of all three building mixes, the district HGSHP systems would ensure lower *TNC* compared to individual HGSHP systems installed for the same buildings (Figure 1). However, the difference between the optimum district and individual *TNC*'s are much higher in the "A+B" mix compared to the other two mixes. This is explained by the significant differences in occupancy regimes of Type A and B buildings (Table 1), so that, when combined, these buildings efficiently share GSHP installed capacities, and maximize the utility of GHEs. Note that in all optimum hybrid cases, significant shares of heating energy are provided from sustainable geothermal sources (Table 4) ensuring low CO_2 emissions from the buildings.

If two buildings with different occupancy rates are connected to a district HGSHP system, the building with a lower overall occupancy rate would benefit more financially from the district arrangement than the building with a higher overall occupancy rate. Indeed, the minimum *TNC* for residential buildings in the “A+A” mix is the same as the minimum *TNC* for buildings in the “A+B” mix, 14.6 £/MWh. At the same time, the minimum *TNC* for office buildings in the “B+B” mix is much higher, 23.1 £/MWh. The minimum *TNC* in the “A+B” mix is 14.6 £/MWh. Hence, Type B buildings would access a much lower total normalised cost of heating if they are in the “A+B” mixes compared to when they are in the “B+B” mixes. However, Type A buildings would also benefit from being in the “A+B” mixes, since such districts would allow them to have lower capital costs compared to the “A+A” mixes (£13,200 in comparison to £19,600, see Table 4) while still accessing the same low *TNC*.

Results demonstrate that building thermal demand regimes must be *combined* when sizing GHEs in order to better optimise district HGSHP systems. Indeed, in the “A+B” mix, the individual HGSHP system would be sized for a shave factor of $\alpha = 47$ % to achieve the minimum *TNC* = 18.7 £/MWh (the minimum of the “Individual” curve in Figure 1c). If the district HGSHP system was designed by designing the GHEs as per individual demands, the GSHP would be sized for the same $\alpha = 47$ % which would result in *TNC* = 15.8 £/MWh. However, if the thermal demand of the buildings is combined, the GSHPs would be sized for $\alpha = 33$ % which would reduce the *TNC* to 14.6 £/MWh (the minimum of the District curve in Figure 1c). In addition, 22 % less of the capital cost would be invested to achieve the minimum *TNC*, £13,200 in comparison to £16,900 (Table 4).

To evaluate risks of investments into HGSHP heating systems, payback periods were calculated. The payback periods were estimated for the optimum configurations of HGSHP systems installed individually and for districts of two buildings as well as for district arrangements when HGSHP systems were sized individually, without combining building thermal demand regimes. The results of the estimation are shown in Figure 2.

From the figure, the initial investments into HGSHP systems of Type A (residential) buildings have significantly lower payback periods compared to the initial investments into HGSHP systems of Type B (office) buildings. For example, for the cases of district arrangements, the payback period for the “A+A” mix is 5.8 years whereas the payback period for the “B+B” mix is much higher, 9.3 years. This is explained by higher annual returns in the “A+A” mixes due to the higher annual heating demands for Type A buildings in comparison to Type B buildings for the same design heating demands (Table 1).

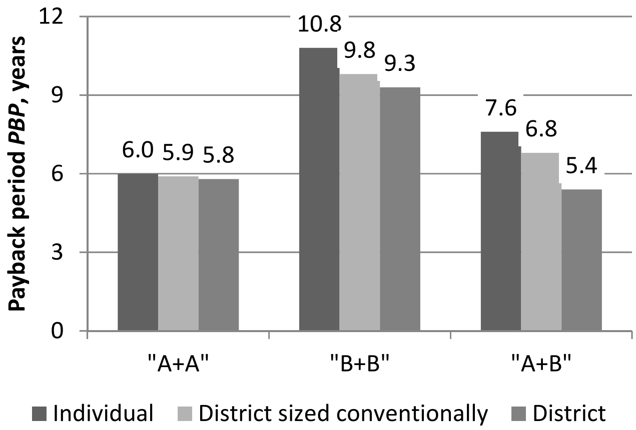

Figure 2. Payback periods for optimum HGSHP configurations for three building mixes: “A + A”, “B + B” and “A + B”.

Among all calculated payback periods presented in Figure 2, the minimum of 5.4 years is expected in the district arrangement of the “A+B” mix. In this mix, both Type A and Type B buildings would benefit from low payback periods as well as from the low capital costs and total normalised costs of heating (Table 4). For the individual as well as for district HGSHP systems sized conventionally, without taking into account building thermal demand regimes, the payback period of the “A+B” mix would be higher, 7.6 and 6.8 years respectively. This, again, demonstrates that district HGSHP systems are more economical than individual HGSHP systems especially when the district systems are optimised with building thermal demand regimes.

The example case presented investigates some general aspects of the optimisation of district HGSHP systems by considering building thermal demand regimes. More research should be performed to quantify thermal demand regimes of typical building mixes based on factors, additional to building occupancy. These detailed heating demand regimes could be used in comprehensive studies of their effects on optimisation of district HGSHP systems. Based on these studies, optimum building mixes can be suggested, so that the minimum total normalised costs of heating, capital investments and payback periods are achieved.

4 CONCLUSIONS

The paper discusses potential financial benefits of district hybrid ground source heat pump (HGSHP) systems in comparison to individual HGSHP systems. A methodology of the financial optimisation of district HGSHP systems was presented where building thermal demand regimes were taken into account to find the optimum share of GSHP systems in the hybrids.

An illustrative example demonstrates the economic advantages of district systems for two building mixes and the importance of combining the building thermal demand regimes when district GHEs are designed. It shows that if buildings with significantly different thermal demand regimes were connected to one (district) HGSHP system, they would benefit financially from such a system arrangement. In particular, their total normalised costs of heating and payback periods would be significantly lower in comparison to individual HGSHP systems.

In addition, the example shows that for the optimum sizing of district HGSHP systems, the building thermal demand regimes have to be combined when sizing the GHEs. If GHEs in such hybrids were sized conventionally, without taking into account the demand regimes, the resultant total normalised costs of heating and capital costs would be higher than at the optimum sizing.

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6 REFERENCES

Alavy M, Nguyen H V, Leong WH, et al. (2013) A methodology and computerized approach for optimizing hybrid ground source heat pump system design. *Renewable Energy*, **57**, 404–412.

Hackel S, Nellis G and Klein S (2009) Optimization of Cooling-Dominated Hybrid Ground-Coupled Heat Pump Systems. *ASHRAE Transactions*, **115**(**1**), 565–580.

Hénault B, Pasquier P and Kummert M (2015) Financial optimization and design of hybrid ground-coupled heat pump systems. *Applied Thermal Engineering*, **93**, 72–82.

Nguyen H V, Law YLE, Alavy M, et al. (2014) An analysis of the factors affecting hybrid ground-source heat pump installation potential in North America. *Applied Energy*, **125**, 28–38.

Ofgem (2016) Non-Domestic RHI Main Guidance. Available from: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-renewable-heat-incentive-rhi (accessed 1 February 2016).

Oxera (2011) Discount rates for low-carbon and renewable generation technologies. Available from: https://www.theccc.org.uk/archive/aws/Renewables Review/Oxera low carbon discount rates 180411.pdf (accessed 1 February 2016).

Philippe M, Bernier M and Marchio D (2010) Sizing Calculation Spreadsheet Vertical Geothermal Borefields. *ASHRAE Journal*, **52**(**7**), 20–28.