Integrated thermal strategies for UK non-domestic building energy demand

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Abstract
Buildings contribute to a third of total CO₂ emissions globally. Further measures to decarbonise buildings are crucially needed to tackle climate change and reach net zero. This paper investigates how building consumes energy in response to the opportunity of adaptive thermal comfort and onsite repurposed geothermal wellbore, under the warming climate. The results show that when both thermal strategies were applied, the building’s energy reliance on non-renewables can be reduced by over a quarter. This work has demonstrated a low-cost viable way of cutting down building’s energy demand and carbon emissions.

Highlights
- Adaptive thermal comfort strategy can curb building energy demand by 16% to 18%
- Repurposed geothermal wellbore can meet over a tenth of building energy demand
- Integrated thermal strategies can reduce over a quarter of building’s reliance on non-renewables
- The percentage in savings through integrated thermal strategies increase slightly over the coming decades

Introduction
The operation of buildings contribute 30% of global energy demand and are responsible for 27% of CO₂ emissions (IEA, 2022). Most of the energy used in buildings is used for heating and cooling to maintain a comfortable indoor environment. Decarbonising heat delivery, alongside energy demand reduction, is therefore crucial in meeting the net zero target (DESNZ & BEIS, 2021). Geothermal energy provides a reliable source of heat among various renewables, having recently gained traction also because of its wide availability.

However, the uptake of geothermal energy has been relatively slow mainly due to the challenging, high risk and high cost of geothermal well drilling. Currently there are millions of abandoned wellbores that can be repurposed and recycled to supply heat to the buildings as geothermal energy (Kurnia et al., 2022). A number of studies have investigated the utilisation and adoption of repurposed geothermal wellbores (Alimonti and Soldo, 2016; Brown et al., 2023b; Kolo et al., 2022; Kurnia et al., 2022; Nian and Cheng, 2018; Roksland et al, 2017; N.M. Wight, N.S. Bennett). Despite these, there is a lack of work evaluating feasibility for a repurposed wellbore to help meet a building’s net zero operation when integrated with other demand reduction and low carbon strategies.

Meanwhile, heating and cooling demands of building are heavily influenced by the management of thermal comfort conditions. For example, an office building might implement strict indoor climate conditions without much adaptive opportunities for occupants. It usually happens in air-conditioned offices where an optimal temperature setting is chosen to maintain the ‘best’ indoor comfort. On the other hand, an adaptive comfort approach encourages users to embrace a wider range of temperatures which in turn reduces building energy demand (de Dear et al., 2013; Nicol et al., 2012). Adaptive comfort has been first put forward through studies on naturally ventilated buildings, where the occupants can be satisfied with a wider range of indoor temperatures pertinent to outdoor temperatures, if they have more control of their environment ( Humphreys et al., 2015). Existing research on adaptive thermal comfort has examined its impact on building energy demand, which shows energy savings of between 32% and 73%, depending on the climatic zone as well as the heating and cooling setpoint temperatures (Spyropoulos and Balaras, 2011; Sánchez-García et al., 2020). However, there is a lack of work evaluating how the impact from an adaptive approach would change under the warming climate, especially concerning cooling demand in the UK (Khosravi et al., 2023). Meanwhile, heat decarbonisation has rarely been considered alongside an adaptive comfort approach. Thus, this work seeks to bring these together, examining the potential of integrated thermal strategies to decarbonise non-domestic buildings, both at present and in a warmer future.

This work aims to evaluate the extent to which integrated thermal strategies including geothermal and adaptive opportunities can reduce building energy demand and reliance on non-renewables. Its novelty resides in bringing both supply and demand sides together to tackle heat decarbonisation at building scale. Its scope is limited to modelling simulation of heating and cooling of office buildings. The objectives include: 1) comparing building energy demand after extending temperature set-points to integrate adaptive thermal comfort; 2) examining future building energy demand, such as how the heating and cooling demands change under the warming climate; 3) evaluating the feasibility to achieve renewable energy supply using a repurposed deep borehole.
Methods

Case study building and borehole

Urban Sciences Building (USB), located at Helix site of Newcastle University in the UK, has been chosen to be the case study (Figure 1). The USB is comprised of more than 12,500m² of laboratory and office space, completed in 2017. It is equipped with an advanced sensor system to serve as a ‘living laboratory’ and full-scale demonstrator of urban innovation. The building has a well-insulated fabric that exceeds the thermal resistance threshold of the statutory requirement (Part L 2013) by 40% (see table 1). Zone target temperatures are updated seasonally and an adjustment range of ±3°C is available to the occupant via wall-mounted thermostats. Water to water heat pumps are used to provide the building heating, cooling and domestic hot water loads. In addition, 9 back up gas boilers in 3 banks of triple units are used during the peak demand to preheat water, to contribute to space heating and domestic hot water need.

![Figure 1: Urban Sciences Building (USB)](https://doi.org/10.26868/25222708.2023.1571)

<table>
<thead>
<tr>
<th>Fabric:</th>
<th>Actual</th>
<th>Statutory requirement</th>
<th>% Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazing (W/m² K)</td>
<td>1.40</td>
<td>2.20</td>
<td>36%</td>
</tr>
<tr>
<td>Walls (W/m² K)</td>
<td>0.17</td>
<td>0.35</td>
<td>51%</td>
</tr>
<tr>
<td>Floor and roof (W/m² K)</td>
<td>0.14</td>
<td>0.25</td>
<td>44%</td>
</tr>
</tbody>
</table>

The adjacent borehole, Newcastle Science Central Deep Geothermal Borehole, has a total depth of 1821m. It is currently not in use, and repurposing this borehole to supply heat to the building has been investigated (Kolo et al., 2022 & 2023; Brown et al., 2023a & b; Younger P. L. et al., 2016). Based on a feasibility study with numerical modelling using OpenGeoSys software to simulate the borehole as a deep borehole heat exchanger, a 65kW heat load can be supported when coupled to a heat pump with a coefficient of performance of 4.33 (Kolo et al., 2023). As this work is emphasising on building simulation, the performance of the borehole is simplified to consider only operational electricity consumption without calculating other investment or operational costs.

Building performance simulation

A validated dynamic physics-based (EnergyPlus via DesignBuilder) model for the USB is used to implement the building performance simulation (Figure 2). This USB model has been derived from the EPSRC-funded project ‘Building as a Power Plant’. Data hosted by the publicly-accessible Newcastle Urban Observatory from advanced metering infrastructure was used to provide calibration and validation to the model (Zirak et al., 2019; Royapoor et al., 2020).

Using this model, this work examines and compares building energy demand variations under strict and adaptive comfort conditions. Strict comfort conditions refer to the case when an office building is fully airconditioned to the optimal level that the indoor temperature has minimum fluctuations. Adaptive comfort conditions, on the other hand, offer opportunities for occupants to control and adapt to their thermal environment by means of clothing, operable windows, etc. In this work, the adaptive comfort conditions are set to a wider range of temperatures, compared with strict comfort criteria (Table 2). These are implemented through central heating and cooling management control system in the form of temperature setting. The strict comfort settings are derived from the optimal temperature for air conditioned office buildings (CIBSE TM40, 2020; Porras-Salazar et al., 2021; Seppänen et al., 2006). Meanwhile, the adaptive comfort settings consider not just minimum and maximum healthy indoor temperatures for occupants but also workplace productivity (ANSI/ASHRAE, 2020; Humphreys et al., 2013; Niemela et al., 2002; Olesen, 2000; Seppänen et al., 2004; Schiller, 1990; Taleghani et al., 2013). By expanding the lower and upper ends of the temperature setting while considering comfort, health and productivity, occupants can then adapt to their environment with a degree of freedom to control their optimal comfort, such as by putting on a jumper, opening or closing windows, using shades and fans.

Table 2: strict vs. adaptive comfort conditions.

<table>
<thead>
<tr>
<th>Thermal strategy</th>
<th>Strict comfort</th>
<th>Adaptive comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating (°C)</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>Cooling (°C)</td>
<td>21.5</td>
<td>24</td>
</tr>
</tbody>
</table>

Building energy demand is further examined under the future weather projections. Due to global warming, external weather conditions are likely to result in much higher cooling and relatively less heating demand for the USB. This work evaluates the extent to which utilising an adaptive thermal comfort strategy can have an impact on heating and cooling demand under the warming climate. The weather profiles for 2030, 2050 and 2080 have been obtained from COLBE - The Creation Of Localized Current and Future Weather for the Built Environment, a repository of future weather for the UK, hosted at the University of Bath. These future weather projections are
compared to a baseline, which is a 10-year average weather file of the 2020s.

Finally, the extent to which geothermal energy can contribute to the total building demand is calculated. This is based on the assumption that the heating season is 6 months per year, outside of which the borehole will rest and recover during the warmer seasons without heat extraction.

**Results**

**Strict vs. adaptive thermal comfort**

A comparison of the baseline building thermal demand from strict and adaptive comfort conditions show that an adaptive approach can almost half the building’s thermal loads. In particular, cooling can be reduced by 72% with an adaptive approach (Table 3 and Figure 3). This shows that when giving occupants the opportunities to adapt to their environment, the resulting energy savings can be significant. Figure 4 and 5 show that the peak cooling demand decreased from 1344 kW to 1145 kW, whereas the peak heating demand decreased from 806 kW to 735 kW, when changing from strict comfort condition to adaptive comfort mode.

In addition, the number of hours needed for cooling significantly reduced from 340 to 148, with an adaptive approach. Meanwhile, heating remained mostly on throughout the heating seasons (4754 and 4226 hours respectively for strict and adaptive comfort modes). In Figure 4 and 5, X-axis shows the number representing 8760 hourly annual data. Despite significant reduction in heating and cooling, the total energy demand only varied by 16% when changing from strict comfort condition to adaptive mode, as shown in Table 3.

**Table 3: comparing energy and thermal demand from strict vs. adaptive comfort**

<table>
<thead>
<tr>
<th></th>
<th>Strict comfort</th>
<th>Adaptive comfort</th>
<th>% savings through adaptive comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating [kWh]</td>
<td>1078463</td>
<td>683534</td>
<td>37%</td>
</tr>
<tr>
<td>Cooling [kWh]</td>
<td>75215</td>
<td>21258</td>
<td>72%</td>
</tr>
<tr>
<td>Total energy use [kWh]</td>
<td>2753597</td>
<td>2304711</td>
<td>16%</td>
</tr>
<tr>
<td>Energy per total building area [kWh/m²]</td>
<td>209</td>
<td>175</td>
<td>16%</td>
</tr>
</tbody>
</table>

**Future building energy demand**

The total energy demand, as well as heating and cooling respectively, are compared in Table 4 and Figure 6, while considering strict vs. adaptive comfort modes and the future climate scenarios (2030, 2050 and 2080). Under all future climate scenarios, the total building energy use decreases, as the need for heating lessens. Despite an increase in cooling demand over the decades, heating remains a much more significant part of overall energy consumption, having still a share of 35% with strict comfort mode and 23% with adaptive mode in 2080. In contrast, even with strict mode, cooling shares only 5% of total energy demand in 2080.
Over the next several decades, the absolute decrease in heating load is considerably larger than the absolute increase in cooling load. In relative terms, however, the annual cooling energy demand for USB will increase by 80% - 271% from baseline to 2080 while the heating energy demand will fall by 13% - 26%.

Furthermore, considering an adaptive approach for building demand reduction, heating was reduced from baseline by 37% in 2030, whereas the cooling reduction was 74%. This reduction by an adaptive approach (compared to baseline) increased to 46% for heating and reduced to 42% for cooling in 2080. Overall energy demand reduction (compared to baseline) of 17% was achieved in 2030 and 2050 with an adaptive approach; and this only increased slightly to 18% in 2080.

With an adaptive comfort approach, cooling demand remains only a very small proportion of overall consumption. It rises from 1.5% in 2030 to 3.6% in 2080. Even with strict comfort mode, the share of cooling only goes up from 4.5% in 2030 to 5.1% in 2080. However, a detailed breakdown of the amount of hours needed to cool the building during the hot weather shows that the role it plays will become more important over the coming decades. The baseline hours for cooling are 343 and 148 for strict and adaptive comfort modes respectively (Figure 4 and 5). Figure 7 and 8 shows that the building will need 424 hours of cooling with strict comfort mode and 195 hours with adaptive mode in 2030. The hours evolve to be 426 (strict) and 211 (adaptive) in 2050 (Figure 9 and 10). These further rises to 493 (strict) and 343 (adaptive) in 2080 (Figure 11 and 12).

Peak thermal demand has an impact on the sizing of heating and cooling technologies. It is notable that the cooling peak demand is significantly larger than the heating peak demand for all scenarios. While the heating peak demand remained just over 800 kWh with a strict comfort setting in 2030, 2050 and 2080, cooling peak demand has varied greatly. Figure 7 and 11 show that a peak demand of 1522 kWh may be reached in 2080, with a strict comfort setting, rising from 1205 kWh in 2030. With an adaptive approach, the peak may be reduced to 1232 kWh in 2080, and 1021 kWh in 2030 (Figure 8 and 12).

Table 4. Demand for heating, cooling and total energy with respect to strict vs adaptive comfort

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2030</th>
<th>2050</th>
<th>2080</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[kWh][strict]</td>
<td>1,062,831</td>
<td>962,368</td>
<td>934,405</td>
</tr>
<tr>
<td>[kWh][adaptive]</td>
<td>671,500</td>
<td>592,411</td>
<td>508,252</td>
</tr>
<tr>
<td>Cooling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[kWh][strict]</td>
<td>126,247</td>
<td>128,870</td>
<td>135,354</td>
</tr>
<tr>
<td>[kWh][adaptive]</td>
<td>33,524</td>
<td>39,142</td>
<td>78,780</td>
</tr>
<tr>
<td>Total energy use</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[kWh][strict]</td>
<td>2,794,835</td>
<td>2,699,336</td>
<td>2,672,421</td>
</tr>
<tr>
<td>[kWh][adaptive]</td>
<td>2,310,780</td>
<td>2,239,651</td>
<td>2,189,128</td>
</tr>
</tbody>
</table>

![Figure 6: USB heating and cooling demand with strict vs. adaptive thermal comfort in future climate scenarios.](https://doi.org/10.26868/25222708.2023.1571)

![Figure 7: USB heating and cooling demand with strict thermal comfort in 2030.](https://doi.org/10.26868/25222708.2023.1571)

![Figure 8: USB heating and cooling demand with adaptive thermal comfort in 2030.](https://doi.org/10.26868/25222708.2023.1571)
Demand met by geothermal energy

The geothermal wellbore is estimated to provide 65 kW heat load to the building. A total heat supply is calculated at 65 kW * 24 h * 182 = 283920 kWh, in which 182 represents the number of days when the heating is on, assuming to be half of the year. Therefore, in order to achieve this, a heat pump with a CoP of 4.33 would use 65,570 kWh of electricity annually. Figure 13 shows that geothermal energy can meet 56% of heating demand in 2080 when adaptive comfort approach is adopted. In contrast, this figure is the smallest at only 26% when strict comfort setting is used at present (baseline). For meeting total energy demand of the building, it remains relatively a small proportion at between 10% and 13% across all scenarios.

Discussion

Overall, the findings suggest that integrated thermal strategies can reduce over a quarter of building’s energy reliance on non-renewables. In particular, they can meet a significant proportion of building’s heat demand. For example, the use of an adaptive approach can almost half the thermal load of the case study building, while the geothermal heat provision can meet more than half of the heating needs in 2080. Nevertheless, for an office building like USB to achieve net zero, further renewable energy supply will still be needed.

The use of an adaptive comfort approach on building thermal management has important implications on cooling. The lessened cooling peak demand would mean lower size requirements for cooling technology, and also help reduce stress on electricity grid and heat network during the heat waves. With adaptive opportunities, building cooling needs in a cooler climate like UK might not be as significant as some studies suggest (Khourchid et al., 2022; Berger et al., 2014; Deroubaix et al., 2021; Frank, 2005; Christensen et al., 2006), despite the warming climate. This is in agreement with a number of studies examining the impact of future climate on heating and cooling in a temperate climate zone (Chow and Levermore, 2010; Jenkins et al., 2008; Larsen et al., 2020; Semmler et al., 2010). However, due to the increase of peak cooling demand and length of hours needed for cooling, low carbon cooling strategies to combat heat waves are thus needed over the next several decades.
Meanwhile, the use of geothermal cooling can serve as a low carbon avenue to meet this need.

Existing work on adaptive thermal comfort strategies considering future climate scenarios has suggested that such strategies can save energy consumption by 50% (Bienvenido-Huertas et al., 2020a; Bienvenido-Huertas et al., 2020b; Sánchez-García et al., 2019). The energy savings from these studies far exceed the results from this study. The main reason is that those studies have looked into hotter climate where cooling has been the main consumption, whereas in this study heating is predominant. Meanwhile, studies examining the capacity of deep borehole heat exchanger has shown varied heat extraction rate in providing heating to buildings, depending on volume flow, well depth, geothermal gradient, the outlet temperature, etc. (Chen, et al., 2021; Bu, et al., 2019; He and Bu, 2020). Admittedly, the building and borehole used as case study in this research have distinct characteristics and differ to various extents from other studies. Such differences would contribute to the variations in the levels of decarbonisation achievable. Nevertheless, this work suggested that integrated thermal strategies are viable for buildings to decarbonise, especially with an adaptive comfort approach where zero cost is incurred in adjusting central management settings in heating and cooling. Further work can consider the alternative renewable source for heating and cooling, such as installing ground source heat pumps where shallow geothermal energy is utilised which may be more applicable for generalised uptake.

The work on geothermal energy provision in this paper is limited to the heat extraction during the heating seasons. Further work on heat injection into the wellbore to provide cooling to the building will be useful to explore the total contribution a geothermal wellbore can make towards a building’s thermal demand, as well as the longitudinal effect of heat injection on the performance of the wellbore. In addition, this paper has assumed that 65 kW heat load provision can remain constant regardless of lowered temperature levels in the borehole as a result of heat extraction. More detailed studies on how this heat provision may change over time is needed, coupled with the effect from heat injection during summer season.

**Conclusion**

This paper has shown that integrated thermal strategies can more than halve a building’s heating and cooling in future climate scenarios. Study of geothermal energy supply from a deep borehole shows that it is possible for a building like USB to reduce energy reliance on non-renewables by more than a quarter when the adaptive thermal comfort approach is applied. Under the future warming climate scenarios, the modelling prediction shows a more significant decrease in heating and, to a lesser extent, increase in cooling demand at USB. However, with an adaptive thermal comfort approach, the prediction reveals a significant decrease in cooling demand during the summer season. Therefore, this work shows that the impact of adaptive thermal comfort is significant in helping buildings to reduce energy demand. This indicates that occupants’ reliance on mechanical cooling need not be as much as one might assume as the weather gets warmer over the coming decades in a temperate climate like UK. Further utilisation of renewable energy supply will be needed for an office building like USB to reach net zero, in addition to the integrated thermal strategies.

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**References**


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**Figure 2:** USB model (EnergyPlus via DesignBuilder) for building performance simulation.