Sensitivity analysis of heating a typical UK dwelling and implications for retrofit design

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Abstract The aim of this research is to quantify the impact of heating set point on space heating energy demand for a typical UK dwelling. Retrofit includes fabric energy efficiency improvements. Energy performance certificates (EPCs) inform the householder of typical savings per measure, but this has previously been found to inaccurately estimate space heating energy demand, leading to errors in 'typical savings' presented to householders. The most sensitive inputs have been found to be temperature set point, followed by fabric efficiency. The BREDEM methodology assumes a temperature of 21°C for nine hours a day, rather than ~16°C and ~20°C found in research. The methods used to inform this study are local sensitivity analysis of the domestic energy model, based on a typical dwelling example with calibrated inputs. This is done using an open calibrated Python model, based on BREDEM. The impact of heating patterns on space heating energy demand are modelled pre retrofit; according to differing heating set points, following wall and loft fabric upgrade and full fabric upgrade. The BREDEM heating set point assumptions lead to space heating energy demand predicted ~50-100 kWh/m²/yr higher than real heating set points. Implications for retrofit design and EPCs are discussed.

1. Introduction
Energy use in households accounts for around a quarter of all energy used in the EU [1]. Heat is the largest energy end-use and only 10% is produced from renewable energy [2], for example less than 1% of UK homes have a heat pump (MHCLG, 2020) and around 40% of UK electricity required to power heat pumps is still generated by fossil fuels [3]. Reducing heat loss by improving building fabric performance is critical for both existing and new buildings if we are to achieve carbon neutral cities [4], especially as reducing fabric heat loss reduces the demand for heat provision. Many existing buildings were built prior to current standards and encompass embodied energy and aesthetic appeal [5]. There is need for safe retrofit of existing homes to ensure they are climate resilient, healthy to occupy and fit for the future, while reducing energy demand and reliance on fossil-fuel energy sources [6]. Retrofit measures can include building fabric and heat interventions to upgrade existing technologies and these are found to have an attributable impact on space heating related energy demand [7, 8].
Decision making on which retrofit measures to install can benefit from data on the energy impact of interventions. However, research in this space has typically targeted policy level decision-making [9, 10]. Yet, householders need to be motivated to make retrofit decisions for individual homes and information they are able to access can influence this and the sequence of installation. The sequencing of measures influences cumulative emissions [11], especially sizing heating systems to suit the envelope performance. Energy Performance Certificates (EPC) are a communication tool that householders receive when buying or renting a property in the UK and include information about energy use, typical energy costs and recommendations on how to reduce energy use, typical energy costs and recommendations on how to reduce energy use [12], with similar models across Europe, governed by the Energy Performance in Buildings Directive [13]. Yet, while the EPC can be used to inform investment decisions for both individual homes and stock level, the process of creating an EPC can lead to measurement errors [14]. Furthermore, the model outputs are sensitive to model input assumptions [15, 16]. Discrepancies with assumed model inputs and actual values lead to the performance gap between predicted and actual energy use; occupant heating behaviour is often overlooked [17, 18].

Sensitivity analysis allows the impact of one or more inputs, on the modelled output, to be understood [19]. This has value when decisions are based on modelled outputs. The approach can be local (one-at-a-time), or global, sensitivity analysis. The model underpinning UK EPCs is the Building Research Establishment’s Domestic Energy Model (BREDEM), also described as the Standard Assessment Procedure (SAP). Previous work on local [15, 16] and global sensitivity analysis of the BREDEM model has found that SAP wall $U$-values and demand temperatures outputs are the far most sensitive parameters and along with SAP roof, window and floor $U$-values, these account for 96% of variation in model outputs [20]. As SAP typically assumes that homes are heated to 21°C for nine hours a day, but previous work has found means ranging between ~16°C and ~20°C [21]. Using insight on energy use behaviour within modelling could improve retrofit advice [22]. However, to date, the space heating energy impact of differing levels of fabric retrofit interventions against variation in heating set point temperature in homes has not been fully examined for individual dwellings, and this paper responds to that gap.

2. Method
The work presented in this paper is based on calibrated modelled results using a Python package of the SAP 2012 (based on the BREDEM methodology), developed and shared openly by Firth and Halls of the Building Energy Research Group (BERG) at Loughborough University (2021) [23]. The calculation is based on a set of arguments based on input data spread across 12 worksheets: 1.Overall Dwelling Dimensions; 2.Ventilation rates; 3.Heat losses and heat loss parameter; 4.Water heating requirement; 5.Internal gains; 6.Solar gains; 7.Mean internal temperature and 8.Space heating requirement; 9.Energy requirements; 10. Fuel costs; 11. SAP rating; 12.CO2 emissions with base case values. The inputs for heat loss parameters are adjusted over three phases, for six different heating set points (16-21°C), as shown in Table 1. The full model inputs used are shared openly via Github: https://github.com/KateSimpson/Using-the-BERG-SAP-2012-model.
Table 1. Model input adjustments for phases A, B and C

| Element     | Area (m²) | U-Value (W/m²K) |
|-------------|-----------|-----------------|
|             | A: Base Case | B: Partial fabric upgrade | C: Full fabric upgrade |
| Door        | 6.2       | 3.0             | 3.0             | 0.80             |
| Windows     | 15.1      | 1.85            | 1.85            | 0.80             |
| Floor       | 41.4      | 1.1             | 1.1             | 0.15             |
| Wall        | 96.7      | 0.68            | 0.30            | 0.15             |
| Roof        | 41.4      | 0.68            | 0.15            | 0.13             |
| Party wall  | 38.5      | 0.5             | 0.5             | 0.5              |

The Python SAP model [23] was set up in Spyder, an interactive programming environment. This followed install via Anaconda of both Spyder [24] and Python version 3.9 [25]. The worksheets were saved as JavaScript Object Notation (JSON) files, starting with a base case and saving multiple versions with edited inputs data. The following command enabled this and resulted in the outputs of energy requirements and SAP ratings:

```python
from sap2012 import calculate_worksheet
import json
with open('inputs.json') as f: inputs=json.load(f)
result=calculate_worksheet(inputs)
print(result['energy_requirements'])
print(result['SAP_rating'])
```

Outputs were saved in comma-separated value (csv) files enabling the creation of charts and data visualisation. The temperature data inputs are based on previous temperature monitoring studies, one based on 249 homes in Leicestershire, finding mean temperature inputs of 16-20°C during heated periods, whereas SAP assumes that homes are heated to 21°C for nine hours a day [21]. The heat loss parameters are based on the typical construction of a 1950s semi-detached dwelling, based on a physical survey of a standard archetype, derived from SAP 2012 data tables (Phase A). The revised inputs are based on minimum requirements for walls and roofs in current UK Building Regulations (Phase B) and pioneering standards such as Norwegian fabric values and Passive House for all fabric elements (Phase C) [26]. The Python SAP model [23] was calibrated with an Excel version of SAP [27] to ensure the results were consistent. The input data was calibrated with both modelled and measured data for space heating energy use, temperature and air leakage for a semi-detached solid-walled 1950s dwelling in the midlands of the UK.

3. Results
The modelled results are based on one typical archetype, a semi-detached solid-walled and suspended floor 1950s dwelling. The potential space heating demand reduction following two levels of fabric intervention are quantified for six different heating set points, as shown in Figure 1. Figure 2 shows energy demand ranges for phases A, B and C.
Figure 1. Space heating energy demand of a semi-detached dwelling base case and following partial and full fabric retrofit, for different heating set points

Figure 2. The range of space heating energy demand predicted between 16°C and 21°C, for the base case, partial fabric and full fabric retrofit

The results in Figure 1 confirm that the potential savings in energy are highly sensitive to heating practices. While a partial fabric retrofit (walls and floors) could almost halve energy demand from ~200 kWh/m²/yr to ~100 kWh/m²/yr, if the householders set their heating at 18°C, the demand reduction would ~130 kWh/m²/yr to ~70 kWh/m²/yr, which would lead to lower financial savings on energy bills with greater potential to recoup the savings in temperature increases. Figure 2 shows energy demand ranges from ~100 kWh/m²/yr prior to fabric upgrade to ~60 kWh/m²/yr for a partial upgrade and ~35 kWh/m²/yr for a full fabric upgrade. This shows there is greater certainty in potential energy demand and subsequent fuel costs, for homes with highly efficient building fabric and less sensitivity to heating demand temperatures.

4. Discussion

The BREDEM tool is used to inform Energy Performance Certificates (EPCs), which in turn inform householders on typical savings from retrofit interventions [12]. However, the model assumptions are not shown on the certificate and there is no range of typical savings given, leading to misleading information. The results within this paper show a large range of space heating energy demand between heating set points from ~100 kWh/m²/yr prior to fabric upgrade to ~60 kWh/m²/yr for a partial upgrade and ~35 kWh/m²/yr for a full fabric upgrade. Therefore, the energy demand implications of heating set point are minimised in a home with a highly efficient fabric (most elements ~0.15 W/m²K), and over two-thirds lower following a partial retrofit that meets the minimum requirements in the building regulations for walls and floor. To avoid EPCs misinforming investments, as previous research has highlighted [21], this information could be communicated to householders and design teams to inform retrofit decision-making and sequencing. Particularly, prior to sizing a heat pump or alternate heat source, relevant to the building envelope performance. Furthermore, if the motivation of householders was to improve comfort but retain existing energy demand, a partial fabric retrofit allows a temperature set point of 20°C to be maintained at a similar energy demand (~90 kWh/m²/yr) to a set point of 16°C prior to fabric retrofit. Therefore, a chart such as this could be used as a discussion tool to evaluate design requirements. While heating practices can change following retrofit, enabling a conversation regarding thermal comfort preferences and practices can lead to retrofit solutions that fit household needs [28] and predicted energy use relevant to their usual heating behaviour.

This work is based on one typical UK archetype, using a local sensitivity analysis of the UK domestic energy model. This work was carried out using an open source model and inputs have been shared openly, enabling reproducibility of this work. The use of open-source tools can assist accelerate progress...
with energy-efficiency and renewables in a digital era by enabling quicker progress and knowledge sharing.

Further work is needed to explore the sensitivity of fabric retrofit interventions per heating set point for a larger range of archetypes. This information can then be used in the design of retrofits. The role of visual charts, or interactive modelling tools can be explored in relation to the influence on household decision-making. However, further information would be required on the insulation material options, their embodied carbon impact and minimizing risks to the existing fabric, structure and internal environment; plus installation details. The inclusion of uncertainty in assumptions within Energy Performance Certificates could be trialled in a study to understand the value of this information to householders, practitioners and design teams.

5. Conclusion

Space heating energy demand pre and post retrofit for a semi-detached solid-walled and suspended floor 1950s dwelling have been presented, with a variation in heating set point, via calibrated modelled results. The BREDEM heating set point assumptions of 21°C for nine hours a day lead to space heating energy demand predicted 50-100 kWh/m²/yr higher than modelled outputs based on previously monitored temperature data. The range of energy demand per temperature set point decreases from ~100 kWh/m²/yr prior to fabric upgrade to ~60 kWh/m²/yr for a partial upgrade and ~35 kWh/m²/yr for a full fabric upgrade. This leads to greater certainty in potential energy demand and subsequent fuel costs for homes with highly efficient fabrics.

The open source calibrated model and tools adopted could accelerate progress with energy efficiency and renewable energy research. Further work could apply the same sensitivity analysis methods to a variety of typical archetypes. This insight could then be shared with householders, installers and design teams to understand the value of this information from their perspective. Quantifying the uncertainty in modelled outputs, based on sensitivity analysis can form part of the process of decision-making towards carbon neutral cities. This work has implications for retrofit design as well as information presented on Energy Performance Certificates.

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