BUILDING PERFORMANCE: FABRIC, IMPACT AND IMPLICATIONS

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ABSTRACT

While some buildings and retrofit projects are achieving significant steps forward, demonstrating their ability to provide thermally resistant and resilient structures, others fail to achieve their target allowing the unwanted flow of heat energy into and out of the building. Maintaining a comfortable internal environment within buildings of poor thermal performance creates an unnecessary impact on the natural environment, adds unwanted emissions and exacerbates the problem of fuel poverty.

Whole building heat loss tests were used to measure the thermal performance of buildings under heated conditions, during the tests the movement of energy around and through the building elements was observed. The 39 tests reveal significant differences in expected performance compared with that actually tested in the field. Heat flowing though some buildings exceeded that designed by over 50%. An overview of the test methods and elements that contribute to this deviation in whole building performance is presented and the impact that this is having on the UK energy demand is calculated.

The potential consequences in carbon and energy required as a result of the difference have also been calculated. The results suggest that with respect to new builds the deviation between fabric expected and actual performance could emit an additional 0.06 mtCO₂eq per annum, based on the conservative estimate of 120,000 dwellings produced equivalent to approximately £14 million in energy bills. Unless addressed this could will affect every new year’s worth of additional stock thus after 25 years the cumulative wasted emissions resulting from the building fabric performance gap could be around 30mtCO₂eq.

Keywords: Building Forensics; Thermal Performance; Zero Carbon Buildings.

1. INTRODUCTION: THEORETICAL ENERGY EFFICIENCY

The value of energy, whether supplied by fossil fuel or through renewable sources increases as the demand per person and the population grows. Intrinsically linked to the value of energy is its cost, not only in terms of finance but resources consumed and emissions generated. Unfortunately, underperforming buildings not only impact on the demand of the energy commodities, increasing their value and supply cost, but carry a direct financial consequence to the building operator and add an unwanted carbon
emissions burden. Buildings should perform as expected and not require additional energy to achieve normal operation (Stafford et al. 2012a; 2012b).

Currently, so few of the existing 22 million homes (CLG, 2011a) in the UK operate close to the standards expected and legislated for that the whole building stock is in need of an upgrade. Meeting the ‘nearly zero’ standard is a challenge. The retrofit market for domestic buildings is estimated at £200 billion over the next 20 years (King, McCombie & Arnold 2012). With an average £10,000 for each building upgrade a spend rate of £7 billion per year is required up to 2019 and £15 billion from 2020 to 2030 (King, et al. 2012). If this money is not to be wasted, the industry must build reliably and with confidence. Unfortunately, the industry has been woefully weak on building quality, especially achieving thermal performance standards.

1.1 Regulatory requirements in Construction: Energy Efficiency Not Tested

Due to the lack of reliable processes for rolling out buildings that operate within tolerance, the consistency and reliability of ‘energy efficient’ buildings and thermal upgrades is proving problematic. The industry produces 120,000 new properties a year (CLG, 2011b; UK Statistics Authority, 2011), not knowing if the standards claimed are being achieved. Currently the mechanisms used to test actual energy consumption do not adequately address thermal performance.

UK Regulations, and much of that across the world, do not require tests of actual building thermal performance. The Standard Assessment Procedure (SAP) that is used in the UK checks the design for compliance with the Building Regulations, specifically addressing the legislative requirement for conservation of fuel and power. However, neither the Regulation nor SAP requires that the whole building actually performs as expected. The Reduced Data SAP (RdSAP) assessments, used for thermal upgrades, also contribute to the machinery that helps determine a building’s environmental impact, although it is based on a scoring and rating systems working from design and basic inspection data. The information from SAP or RdSAP is used, as part of the data, to rate the building’s performance from A – G, within an Energy Performance Certificate (EPC). At the moment EPC’s are comparative tools, offering a simple ‘expected’ energy performance; they offer a mechanism to compare one building’s expected energy efficiency to another, but do not show the buildings actual efficiency.

Although, not applicable to domestic buildings, the Display Energy Certificates (required for public buildings greater than 1000m²) do show actual energy usage, and while this improves the transparency, it does not provide information on the building fabric or services performance. DECs provide space heating energy demand as a result of the combined impact of the building fabric, services and occupants. The effectiveness of the fabric and efficiency of the services are fundamental. If building fabrics and services underperform, additional energy will be consumed to achieve the relative comfort of a functioning building. Where there are significant defects in the building and service operation it may not be possible to achieve reasonable comfort conditions.
While it may not be appropriate to test the building performance of all buildings, it is essential that further information is gathered through sampling the buildings, prototypes and retrofit innovations. Feedback on improvements and interventions is essential. Understanding characteristic behaviour under different conditions is fundamental to improving building performance.

1.2 Comparisons with other industries: Testing of energy efficiency

Regulated home appliances such as refrigerators are thoroughly tested, only having their relative energy rating awarded once the kWh/year efficiency is known. The European Commission Directive (EUE-LEX 2012) and resulting UK Energy Conservation regulation (HMSO 2004) dictates that:

“6 (1) No supplier shall place on the community market a regulated appliance unless he has established technical documentation sufficient to enable the accuracy of the information contained in a label or information sheet…”

The technical documents referred to shall include, amongst other criteria, relevant measurement tests performed, under harmonised standards, calculations and details of mathematical models for calculating performance.

In time, the construction industry may not be able to avoid adopting similar standards. The Kyoto Protocol is influencing all European Directives. Even where the current EPDB is not quite so prescriptive, regulation will eventually evolve and the legislation of each country will ensure that all products, including buildings, perform to that specified, contracted or to the performance criteria which has been insured under warrantee. With few exceptions, the construction industry does not know how buildings really measure up to the standards and what needs to be done to ensure that buildings are not substandard.

While the industry does not routinely measure the thermal performance of buildings, as the cost of energy rises users increasingly demand information on energy efficiency. The introduction of smart meters brings the possibility to explore energy use during occupied and unoccupied periods. Through further work to disaggregate the energy signatures of the fabric, services and occupants eventually performance information can be fed back to the user without the need for scientific testing. The disaggregation of in-use data to explore building fabric performance has been undertaken with limited degrees of success (Sutton et al 2011), further exploration of the methods below and their relationship with energy signatures uncovered will, in time, provide detailed information on performance. Currently, few research projects are collecting the breadth of data that has the potential to provide the insight required. The methods described below provide an insight to the data that can be collected and over time it is expected that the knowledge gained will help to inform construction professional and, via smart metering and other intelligent systems, the information will be fed in an understandable format directly to the user or facility manager.
There is much to learn with regard to the effective and efficient performance of buildings. The collection and disaggregation of data based on building, services and occupant behaviour should eventually enable feedback allowing occupants the ability to see if they are using the building efficiently and if the building and services are operating as required.

2.1 MEASUREMENT METHOD: MEASURING ACTUAL BUILDING PERFORMANCE

The actual performance of a building can be assessed through scientific field tests such as those used in Technology Strategy Board – Building Performance Evaluation Programmes (TSB 2013) and those conducted by the CeBE group at Leeds Sustainability Institute (LSi, 2013; Gorse et al. 2012). Discussion surrounding building forensics and whole building testing can be found through Annex 58 of the International Energy Institute and on the Leeds Sustainability Institute web pages (Fletcher et al. 2012; Lsi 2013; Sutton et al. 2012). Measurements of the overall building performance are useful to determine the amount of actual energy required to heat and cool a building. Also forensic investigations are important to determine reasons for underperformance if a deviation is found. To understand why a building underperforms information is required on each element, component and junctions that form the whole building. The forensic investigation methods can also provide significant information and identify the actual cause of the discrepancy.

The coheating test determines the actual heat loss through the building envelope. This is achieved by heating the internal environment to an elevated temperature and maintaining the temperature. As the external temperature changes, the power input into the dwelling responds to maintain a stable temperature. As the outside temperature drops more energy is required to heat the dwelling and as the outside temperature rises less energy is required. By monitoring the power input against temperature differential between internal and external environments, the heat transfer through the building can be calculated. Losses due to ventilation, heat gains from solar and variations due to the wind are also considered within the calculations (Johnston et al. 2013). Thirty nine coheating tests were used to measure the thermal performance of new buildings and existing buildings, before and after interventions were made. A summary of the heat loss coefficient is presented in Figure 1. The graph shows that the buildings predicted heat loss is lower than that achieved. There are a few exceptions to this, occurring where the initial understanding of the fabric construction was inaccurate. Due to an underestimate of the fabrics thermal performance, the predicted heat loss in this case exceeded that measured. It is important that the design information fed into assessments is correct, where design information is missing full building surveys and forensic investigations are important to determine the construction of the building’s.
2.1 Forensic Investigation

Forensic investigations were used as a diagnostic tool to identify the cause and effects of building failures or underperformance. The investigation of buildings is critical when trying to understand why certain results have been obtained. Whereas other tests provide context and identify anomalous results, it is the forensic investigation that identifies the actual defects that are responsible for any deviations found. A range of different forensic investigative techniques have been undertaken in these studies.

2.2 Construction Analysis

When testing new build properties regular visits are made during the construction process to make observations as the building is being built, renovated or retrofitted. The timeline images of the construction process can be particularly revealing when attempting to determine causes of poor performance. Still photographic and video images are recorded at key stages. By regularly visiting properties to be tested during the construction phase, factors such as design change, material modification and poor workmanship can be identified, and help with determining any later performance problems. If unexpected heat flow is recorded or found through thermocouple, heat flux readings or observed using thermography, a review of drawings and photographic material may expose the reason for the heat flow or air movement.

2.3 Heat Flow Through Building Elements

Interpreting the energy performance of a building element based on the stated U-values of building elements is often unreliable because the stated U-values come from measurements made under standard laboratory conditions. In reality, the U-value within an element may vary considerably. In situ measurement can be made using heat flux sensors in combination with temperature sensors. Heat flux sensors were used to
measure the rate at which heat passes through a material or building element. This data, together with data for the difference between internal and external temperature, can then be used to calculate an apparent In Situ U-value. By calculating in situ U-values it is possible to not only ascertain the actual performance of building elements, but to identify areas which are performing particularly poorly.

![Figure 1: Equipment for wall forensics: Differential pressure sensors, heat flux plates, surface and internal thermocouples, air flow transducer](image)

2.4 AIRTIGHTNESS TESTING
As air leakage or infiltration is a major factor in building heat loss, air tightness is an important consideration. Unlike ventilation, which is the intentional and controlled flow of air through a property to maintain the safety and comfort of the occupants, air leakage is uncontrolled air flow through gaps/cracks, leading to draughts, heat loss and heat gain. Leaks are often obscured from vision by internal finishes or external cladding, and so correct methods must be used for adequate assessment. The leakage may be observed using handheld smoke puffers or filling the building with smoke and pressurising, or through thermography under dwelling depressurisation, and may be quantified using anemometers and differential manometers.

2.5 THERMAL IMAGING
Thermal imaging is useful for assessing the In Situ thermal performance of buildings, and provides an effective visual representation of heat losses. Thermal imaging identifies the warmer and cooler regions of a surface, and so assists in the understanding of thermal losses from a building. For example, thermal imaging may highlight colder areas of an external wall when viewing from the inside, which would suggest the presence of a thermal bypass, missing insulation or perhaps variations in moisture content. From this indication, further tests such as applying heat flux sensors, air flow sensors or hygrometers to the region can then further investigate possible regions for a cooler area. It is in this sense, therefore, that thermal imaging operates with the same scope as that of standard photographic data, as a tool to aid decisions about subsequent tests.
Figure 2: Thermography showing cold air movement and cold spots under depressurized conditions.

2.6 BUILDING PERFORMANCE MODELLING

In the context of full building testing, modelling offers potential to inform and optimise physical test procedures. By understanding the interactions on a theoretical scale, features of testing such as sensor location and equipment positioning can be optimised to ensure the highest level of accuracy.

In the evaluation of the building and elements, computer modelling software is used to determine projected performance of construction details and whole buildings, with calculations based on the performance of individual materials, usage and exposure. This is particularly useful when assessing the thermal performance of a property and individual elements in different locations, under different conditions and different climates or to model the impact of defects, alterations and improvements.

2.7 IN-USE MONITORING AND BUILDING USER SURVEYS

In-use monitoring is a final stage of full scale testing, obtaining data on completed buildings under realistic occupation. Such testing can be particularly revealing with regards to occupant behaviour, and also gives information on the energy use of internal appliances. Furthermore, in-use testing allows the performance of technologies such as mechanical ventilation heat recovery (MVHR) devices and photovoltaic panels to be assessed.

A wide range of data can be obtained from occupied buildings, based on the needs of the research. This can be as broad as looking at total energy use, or as specific as isolating particular appliances within the home to assess their individual contribution. In-use data can then be used to inform interested parties on building performance and the effect of occupants on this. In-use monitoring studies have also been combined with building fabric performance assessing the ability to separate the effects of building fabric under occupied conditions (Sutton et al. 2011).

2.8 SAMPLE OF RESULTS FROM THE BUILDING FORENSICS

All reports that have been made public and fully describe the observations made during the building forensics process can be found in the documents on the LSi (2013) web page, a further summary and discussion can be found in Gorse et al. (2012)
The problems identified in Table 1 are a result or combination of poor coordination, management, sequencing, workmanship, design and buildability. Product substitutions, poor information management and inadequate attention to the detailing of component interfaces also contributed to some of the problems. The following list represents an insight into some of the problems found that led to significant thermal bridging, bypass and airtightness problems as well as component failure. The list is not exhaustive.

Table 1: Thermal Performance: Management, Inspection and Supervision Issues

Some common problems observed

- Displaced or incorrectly fitted insulation allows thermal bypass. Where rigid partial fill insulation was used it was pushed off the surface of the wall creating voids around the insulation, allowing free flowing air. With changes in weather and other phenomena that affect air pressure, the movement of air and heat energy bypasses and circumvents the insulation.
- Discontinuity of insulation. Obstructions meant that there were gaps in the insulation. The irregularity of surface to which the insulations was placed prevented a close fit.
- Construction interfaces, that required cuts to the insulation to ensure a complete covering were overlooked or poorly fitted.
- Gaps found in cavity socks thus failing to provide an effective continuous seal.
- Insulation not placed properly, not butted up together and not built up to the correct thickness.
- Air, moisture and vapour barriers installed and then punctured to provide service entries, preventing the barrier to function properly. Uncontrolled air movement leads to thermal transfer, bypass and moisture movement within the fabric.
- Insulation was sometimes removed to fit services and not properly reinstated.
- Complicated and difficult to build designs created difficulties and poor quality product.
- Modifications made to the design can result in changes to the size of components. Fitting components with different sizes to that specified meant they were either too small, resulting in gaps, or too large, needing to be cut.
- Air barriers and vapour control layers were sometimes fixed in the wrong positions making them ineffective. The correct interface between the air and thermal barrier is important.
- In some cases instructions were not provided on how to seal barriers around fittings, penetrations and junctions. Folding and layering of building fabrics, such as vapour barriers, is problematic. Multiple layering to make up joints around corners and junctions needs some thought to make an effective seal without excessive build up.
- Incorrect use of tapes and sealants was common, specialist tapes are needed for different surfaces.
- Prefabricated components, such as windows and loft hatches sometimes did not effectively seal.
- Services were positioned too close to the wall making it difficult to seal behind them.
- Hidden services were rarely air-sealed.
- Mortar beds were not filled and the gaps in the fabric were sometimes not sealed.
- Sealing coats only applied to open easy to access faces.
- Gap sealants were applied at surface level rather than properly fed into the gap.
- Incorrect lifting and moving of prefabricated structurally insulated panels caused damage.
- Incorrect expansion strips were sometimes used, making an ineffective seal.
- Junctions were not sealed. Points of air-leakage and infiltration were found around thresholds, windows and doors, between frame and breather membranes, around and through roof lights, roof panels, at the ridge, eaves and between roof panels.
- Air leakage was found around light roses, electrical sockets and other service fittings.
- Air leakage occurred through flooring panels that were damaged and poorly sealed.

2.8 INTERVENTIONS AND EFFECTS

Throughout all of the studies there have been efforts to feedback knowledge to designers, contractors and manufacturers. Improvements have been made and new interventions tested. The Temple Avenue project (CeBE 2010) is a typical example of staged intervention demonstrating the improvements that can be made. A 1930's property improved to the same standard as two energy efficient prototypes. Another example from the study is the party wall intervention shown below. Prior to the insertion of full cavity insulation, the partially filled cavity was allowing free flow of air and considerable thermal bypass, following the intervention the fabric exhibits control over the thermal movement and significantly reduces the effective heat flow.

The results show significant improvements to the thermal performance of the wall. Prior to the intervention of full fill insulation the wall failed to provide an effective barrier to the outside elements. The variability of the heat flow before the insulation fill was introduced suggests that the wall is not effectively sealed, is experiences problems due to air infiltration, possible bypasses and general breaches of the building fabric. Building envelopes that do not offer constant thermal resistance will experience uncontrollable heat transfer through the fabric during cold and hot days. Variable wind pressure and direction also have a dynamic and adverse effect on such fabrics. The graph (figure 3) shows how insulation added to existing walls can create a consistent and performing fabric offering the desired resistance and creating a separation between internal and external environment condition.
Figure 3: A partially filled cavity exhibiting characteristic signs of thermal bypass and air movement, the full fill intervention creates a fabric that controls movement and significantly reduces heat flow. (Courtesy Leeds Metropolitan University and Knauf Insulation Building Physics Research)

The building forensic and heat loss studies have been met with questions regarding the relative cost of the performance gaps and the benefits in financial terms if interventions are made. Equally, the question has been raised as to the likelihood of financial incentive schemes introduced by the UK government and the potential of them being effective if gaps in performance are common. The remainder of the paper attempts to address some of the related issues associated with the UK government’s Green Deal (DECC 2012a; 2012b).

3.0 FINANCIAL AND POLICY INCENTIVES FOR CHANGE AND IMPLICATIONS

Historic energy bills and data derived from their National Energy Efficiency Data-framework (NEED) has been used by the Department for Energy and Climate Change (DECC) to assess the amount of carbon actually saved by eco-renovation schemes compared to emissions that were predicted by the calculation engine SAP. They concluded the measures underperformed in reducing domestic space heating by around 50% of their technical potential (DECC 2012b) referred to as a ‘performance gap’. This analysis informed predictions for new policy launched in 2012, the Green Deal.
The performance gap therefore manifests as underachievement of policy. The Green Deal implemented in 2012 is intended to provide a large scale upgrade of the existing inefficient housing stock and assumes this default performance gap of around 50% for each retrofit. Reducing this would have great implications in terms of carbon and cost. In the UK the Green Deal was implemented to provide loans to householders so that they can install at no or low upfront cost eco-improvement measures like insulation and condensing boilers which may be repaid heating bill reductions. The performance gap jeopardises this policy mechanism. Aligning actual energy reductions with predicted savings therefore is paramount to the Green Deal’s perceived success and the ability of householders to payback loans without incurring excessing interest repayments.

### 3.1 Financial and Policy Research Method

Using a scaled down or ‘corrected’ energy saving estimates in policy to mimic the performance gap is achieved using an ‘in-use factor’. This phenomenon was first observed by the Homes Energy Efficiency Database (HEED) which showed previous similar schemes such as the Energy Efficiency Commitment (EEC) and Carbon Emissions Reduction Target (CERT), both designed to encouraging greater uptake of home insulation and more efficient boilers were not as effective as initially predicted. A performance gap of around 50% on average was observed using energy bills before and after measures were observed the impact of this on the Green Deal is shown in Table 1.

#### Table 1: Green Deal GHG savings in 2022 (Derived from DECC 2012b)

<table>
<thead>
<tr>
<th>Insulation type</th>
<th>Savings / household</th>
<th>Corrected savings</th>
<th>Performance Gap %</th>
<th>Number of households</th>
<th>National GHG saving (mtCO₂eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Wall 1</td>
<td>7,945 kWh</td>
<td>4,373 kWh</td>
<td>55%</td>
<td>955,902</td>
<td>0.767</td>
</tr>
<tr>
<td>Cavity Wall</td>
<td>4,569 kWh</td>
<td>2,272 kWh</td>
<td>50%</td>
<td>2,517,009</td>
<td>1.050</td>
</tr>
<tr>
<td>Loft</td>
<td>845 kWh</td>
<td>424 kWh</td>
<td>50%</td>
<td>1,640,000</td>
<td>0.128</td>
</tr>
</tbody>
</table>

The reasons for this performance gap are not explored in detail in their report but are supposed to be due to insulation’s underperformance (perhaps due to improper installation or fabric failure), SAP’s assumptions being unrealistic compared to actual buildings, and some walls being inaccessible for installation to be fitted. The concept of ‘comfort taking’ is also mentioned as a cause whereby householders will enjoy warmer homes (as a result of insulation) rather than make reductions to their energy use. The rank importance of these factors contributing to the performance gap remains unknown. Acknowledgement of the performance gap in the Green Deal predictions raises the question why a similar ‘in use factor’ approach is not applied when using SAP for other energy prediction purposes such as in Building Regulations compliance.

This research attempts to identify how much of the gap is attributed to building fabric. It draws on the 39 coheating tests shown in Section 2.1 of this paper and these heat loss data form the basis of annual energy consumption estimates calculated using

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1 Average of three SWI types
degree days data for York\textsuperscript{2} (assuming a base temperature of 15.5°C) according to the CIBSE TM41 (2006) guide where::

\[
\text{Heat Demand (kWh)} = \text{Degree days x Heat loss (W/K) x 1000(W) x 24(h)}
\]

(Eq: 01)

The 2013 Carbon Trust default conversion value of 0.1824 kgCO\textsubscript{2}eq / kWh of gas is used to derive the resulting carbon emissions assuming a system efficiency of 80% and ignoring other incidental gains and losses. Then benefits of using these data are that the assessments were undertaken on unoccupied properties that were intensively studied and whose thermal properties were being deliberately upgrade, thus the influence form occupants enjoying ‘comfort taking’ and any errors due to inaccessibility can be disregarded when interpreting the results. Similarly ventilation assumptions in SAP used to predict heat loss have been replaced by actual measurements in this data thus further reducing errors via model assumption accuracy. Thus this assessment is an accurate reflection of the influence on the performance gap caused by the quality of building fabrics and their installation. This form of micro research supports the macro approach taken by DECC, which can only identifying the scale of the gap not its cause.

3.1 \textbf{FINANCIAL AND POLICY RESEARCH RESULTS AND DISCUSSION}

Table 2 shows a relationship for heat loss data if considered in carbon, dwellings are anonymous for purposes of data protection. It is notable that the predicted emissions were almost always lower than the measured. The range of the ‘fabric-only’ derived heat loss performance gap identified was between -9% and 58% across the sample. This implies that insulation material and installation quality can have a significant but variable impact on the performance gap. Where the measured performance was in fact greater than the predicted a negative value is recorded.

\textsuperscript{2}Gillygate, York, ENGLAND, UNITED KINGDOM (1.08W,53.97N) www.dgreedays.net based on 15.5oC and 22months (August 2011 to May 2013)
### Table 2: Performance gap of eco-refurbishments and eco-new builds (taken from CeBE)

<table>
<thead>
<tr>
<th>Household</th>
<th>Heat loss measured and predicted (W/K)</th>
<th>Predicted space heating demand (kWh/annum)</th>
<th>Measured(^a) heat demand (kWh/annum)</th>
<th>Additional Emissions/m(^2) (kgCO(_2)eq)(^4)</th>
<th>Performance gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49.7</td>
<td>3,421</td>
<td>6,776</td>
<td>2.48</td>
<td>44%</td>
</tr>
<tr>
<td>2</td>
<td>73.7</td>
<td>4,398</td>
<td>9,854</td>
<td>4.05</td>
<td>48%</td>
</tr>
<tr>
<td>3</td>
<td>99.4</td>
<td>4,889</td>
<td>11,802</td>
<td>4.35</td>
<td>53%</td>
</tr>
<tr>
<td>4</td>
<td>72.2</td>
<td>4,889</td>
<td>10,301</td>
<td>3.16</td>
<td>45%</td>
</tr>
<tr>
<td>5</td>
<td>93.3</td>
<td>5,512</td>
<td>11,664</td>
<td>2.95</td>
<td>48%</td>
</tr>
<tr>
<td>6</td>
<td>66.1</td>
<td>5,512</td>
<td>10,163</td>
<td>2.09</td>
<td>40%</td>
</tr>
<tr>
<td>7</td>
<td>43.2</td>
<td>3,333</td>
<td>6,240</td>
<td>2.16</td>
<td>42%</td>
</tr>
<tr>
<td>8</td>
<td>33.9</td>
<td>3,333</td>
<td>5,727</td>
<td>1.69</td>
<td>36%</td>
</tr>
<tr>
<td>9</td>
<td>48.1</td>
<td>3,410</td>
<td>6,665</td>
<td>2.40</td>
<td>44%</td>
</tr>
<tr>
<td>10</td>
<td>40.0</td>
<td>3,410</td>
<td>6,218</td>
<td>2.00</td>
<td>39%</td>
</tr>
<tr>
<td>11</td>
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<td>7,018</td>
<td>12,304</td>
<td>2.29</td>
<td>35%</td>
</tr>
<tr>
<td>12</td>
<td>97.3</td>
<td>7,272</td>
<td>15,008</td>
<td>3.94</td>
<td>42%</td>
</tr>
<tr>
<td>13</td>
<td>52.2</td>
<td>7,680</td>
<td>13,336</td>
<td>2.11</td>
<td>27%</td>
</tr>
<tr>
<td>14</td>
<td>122.8</td>
<td>5,396</td>
<td>14,081</td>
<td>7.51</td>
<td>56%</td>
</tr>
<tr>
<td>15</td>
<td>87.2</td>
<td>5,656</td>
<td>12,635</td>
<td>5.33</td>
<td>46%</td>
</tr>
<tr>
<td>16</td>
<td>10.9</td>
<td>7,051</td>
<td>9,363</td>
<td>0.44</td>
<td>8%</td>
</tr>
<tr>
<td>17</td>
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<td>7,217</td>
<td>8,972</td>
<td>-0.09</td>
<td>-2%</td>
</tr>
<tr>
<td>18</td>
<td>12.0</td>
<td>8,100</td>
<td>10,792</td>
<td>0.46</td>
<td>8%</td>
</tr>
<tr>
<td>19</td>
<td>-1.6</td>
<td>8,370</td>
<td>10,583</td>
<td>-0.06</td>
<td>-1%</td>
</tr>
<tr>
<td>20</td>
<td>19.6</td>
<td>7,167</td>
<td>9,761</td>
<td>0.47</td>
<td>13%</td>
</tr>
<tr>
<td>21</td>
<td>14.5</td>
<td>6,533</td>
<td>8,199</td>
<td>0.33</td>
<td>11%</td>
</tr>
<tr>
<td>22</td>
<td>-28.2</td>
<td>19,383</td>
<td>22,412</td>
<td>-0.84</td>
<td>-9%</td>
</tr>
<tr>
<td>23</td>
<td>4.6</td>
<td>13,143</td>
<td>15,687</td>
<td>0.14</td>
<td>2%</td>
</tr>
<tr>
<td>24</td>
<td>46.1</td>
<td>5,595</td>
<td>9,374</td>
<td>1.37</td>
<td>31%</td>
</tr>
<tr>
<td>25</td>
<td>-6.2</td>
<td>9,590</td>
<td>10,086</td>
<td>-0.27</td>
<td>-4%</td>
</tr>
<tr>
<td>26</td>
<td>25.8</td>
<td>8,177</td>
<td>12,293</td>
<td>0.96</td>
<td>15%</td>
</tr>
<tr>
<td>27</td>
<td>39.7</td>
<td>8,210</td>
<td>11,797</td>
<td>1.10</td>
<td>21%</td>
</tr>
<tr>
<td>28</td>
<td>57.2</td>
<td>12,404</td>
<td>18,854</td>
<td>1.22</td>
<td>20%</td>
</tr>
<tr>
<td>29</td>
<td>94</td>
<td>5,849</td>
<td>12,492</td>
<td>4.28</td>
<td>47%</td>
</tr>
<tr>
<td>30</td>
<td>32.8</td>
<td>5,849</td>
<td>9,115</td>
<td>1.49</td>
<td>24%</td>
</tr>
<tr>
<td>31</td>
<td>9.6</td>
<td>5,672</td>
<td>7,614</td>
<td>0.44</td>
<td>9%</td>
</tr>
<tr>
<td>32</td>
<td>123.5</td>
<td>4,872</td>
<td>13,066</td>
<td>5.62</td>
<td>58%</td>
</tr>
<tr>
<td>33</td>
<td>30.9</td>
<td>4,878</td>
<td>7,967</td>
<td>1.41</td>
<td>26%</td>
</tr>
<tr>
<td>34</td>
<td>7.9</td>
<td>4,944</td>
<td>6,886</td>
<td>0.36</td>
<td>8%</td>
</tr>
<tr>
<td>35</td>
<td>85.6</td>
<td>7,449</td>
<td>13,943</td>
<td>1.55</td>
<td>39%</td>
</tr>
<tr>
<td>36</td>
<td>44.3</td>
<td>7,090</td>
<td>10,875</td>
<td>1.59</td>
<td>26%</td>
</tr>
<tr>
<td>37</td>
<td>20.3</td>
<td>7,090</td>
<td>9,551</td>
<td>0.73</td>
<td>14%</td>
</tr>
<tr>
<td>38</td>
<td>3.25</td>
<td>2,395</td>
<td>2,745</td>
<td>0.12</td>
<td>7%</td>
</tr>
<tr>
<td>39</td>
<td>1.5</td>
<td>2,019</td>
<td>2,328</td>
<td>0.07</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>26%</td>
</tr>
</tbody>
</table>

\(^a\) based upon a calculation involving measured data and assumptions regarding heating patterns

\(^4\)Assumes system efficiency of 80% and excludes incidental gains or losses
The average performance gap is 26% which validates to an extent the scale of DECC’s assumption that around 50% of the predicted emissions will not be achieved, though additional research into the remaining 24% is needed and further studies may inform how useful an average gap is considering variations in housing stock, age, type and condition are great. The performance gap shown here may be lower than DECC’s estimate for two reasons; 1) Firstly it excludes the other factors influencing the performance gap an 2) the properties presented here are all aspirational low-carbon homes and were aware the study was taking place. This means their eco-measures may have been more carefully installed than normal and it may be argued the performance gap would have been higher if these properties were randomly selected.

The fact that the performance gap was still sizable despite giving advanced notice to installers shows that the ‘fabric-only’ performance gap may not be due simply to complacency or use of lower specification materials but that there may be fundamental structural or technical impediments to the accurate installation of insulation and that current best practice may not be fit for purpose.

Assuming the consumption figures in Table 1 are accurate the gap caused directly by insulation quality and installation may therefore be equivalent to savings of 1 mtCO$_2$eq / annum in 2022, for the 5 million homes estimated to take part in the Green Deal by its final, around £222 million (assuming on £0.04/kWh in 2013). In addition if roughly 120,000 new homes are built annually in the UK with an estimated annual gas use according to Ofgem (2011) of 16,500kWh (of which space heating makes up only two thirds) then extrapolating the observed performance gap of 26% discovered here due specifically to insulation materials and their installation means that perhaps an additional 0.06mtCO$_2$eq (£14 million or £115 per house) is unnecessarily being emitted (spent) by new houses every year. Unchecked this will occur for every new year’s worth of additional stock thus after 25 years the cumulative wasted emissions could be around 19.5mtCO$_2$eq.

This data set is small, the extrapolations are large and do not pay heed to difference in building construction types or changes in climate among many other factors. The results are not normally distributed and there is a high degree of sample variation since the other influences mentioned and building specific characteristics can vary enormously. It is recommended more data be collected on the performance of insulation materials and their installation before these numbers can be considered authoritative but the highlight the issues well. Accurate building simulation assumption, understanding occupant behaviour including comfort taking as well as on surmounting the physical obstacles that can limit the installation of eco-measures in homes also need further investigation before the performance gap can be fully tackled.

4.0 CONCLUSION
The paper has provided a brief introduction into the UK Building Regulations relating to energy and conservation. To meet the zero carbon standards it is clear that considerable change to the thermal performance is required and that the current method of validation which considers only the designed building performance is ineffective because of the performance gap. The case is made that post construction
building forensics could placate this. It is anticipated that the regulatory framework will change to require improved performance. The testing methods show that it is possible to achieve low carbon buildings. Where deviation in thermal performance occurs it is possible, through forensic measures, to identify the contributing factors, undertake remedial measures and feedback information to improve the design and building performance.

Currently fiscal measures are being used to promote change (the Green Deal), the question is raised whether the measures adequately account for the performance gap. The research has shown that the application of an in-use factor by DECC of around 50% to revise down the Green Deal’s carbon emissions savings predictions is a valid approach. Such an acknowledgement is not made in other regulatory spheres such as building regulations for retrofits and new builds, undermining policy goals for carbon reductions. This research highlights that the major factor in the performance gap is likely to be due specifically to the quality of insulation materials and their installation, causing a gap on average of 26%. However it also highlights the heterogeneous nature of buildings and the fabric performance gap may be as high as 58% or as low as -9%.

Greater acceptance and appreciation of the performance gap in the wider built environment could improve aspects of policy, Building Regulations and research and wider benefits surrounding reducing fuel poverty. The variability within the sample and sparseness of data presented here highlights the need for more research in this area to further refine the definition of the factors that contribute to the performance gap and identify their rank importance so that work can begin on minimising the performance gap and reducing carbon emission from buildings.

A significant concern is that if the sizeable nature of the performance gap continues, the cumulative impact in emissions is considerable.

6.0 REFERENCES


DECC( 2012a), National Energy Efficiency Data-Framework, Summary of analysis using the National Energy Efficiency Data-Framework


