GHA Monitoring Programme 2011-13: Technical Report

Results from Phase 2: Post-occupation testing of a sample of sustainable new homes

May 2014

Author:

Christopher Eaton (chris@goodhomes.org.uk)

Good Homes Alliance

The Foundry

5 Baldwin Terrace

London N1 7RU

020 7704 3503

info@goodhomes.org.uk

Front cover image: One Brighton; Derwenthorpe prototypes (Temple Avenue) (image Richards Partington Architects); Old Apple Store (image Ecos Homes)

Acknowledgements

The Good Homes Alliance would like to thank those who assisted in helping to produce this project report and who have made this project possible. This includes the house builders at the four test properties. Particular thanks are extended to the testing team from Leeds Metropolitan University, Oxford Brookes University and University College London. The Good Homes Alliance would also like to thank the Department for Communities and Local Government, (CLG) and the Energy Saving Trust, (EST) for providing funding to help support the Good Homes Alliance Monitoring Programme.

The project was guided by members of the Monitoring Programme Advisory Group including:

- Kingerlee Homes
- Greenoak Housing
- AECOM
- Useable Buildings Trust
- Baily Garner
- Technology Strategy Board
- National House Building Council
- A & G Architects
- Zero Carbon Hub
- BioRegional Quintain
- Ecos Homes
- Joseph Rowntree Housing Trust

This report was written by Christopher Eaton of the Good Homes Alliance. Results and conclusions are based on the findings in the individual site reports, prepared by research teams at Leeds Metropolitan University, Oxford Brookes University and University College London. These teams consisted of David Farmer, Dr David Johnston, Ruth Sutton, and Anne Stafford from Leeds Metropolitan University; Professor Rajat Gupta, Chris Kendrick and Rohini Cherian from Oxford Brookes University; and Dr Hector Altamirano Medina and Professor Robert Lowe from University College London. Thanks also to Dr Fionn Stevenson, Dr Jez Wingfield, and Dr Ian Ridley for their guidance and aid with the first phase of the programme.

Good Homes Alliance Monitoring Programme 2011-13:

Technical Report

Results from Phase 2: Post-Occupation Testing of a Sample of Sustainable New Homes

Table of Contents

1. Executive Summary

The Government has set ambitious regulatory standards for housing developments. Houses have been built which were designed to be very low or zero carbon. However many low or zero carbon solutions are untested in-use, and there is growing awareness within the housing industry that current energy efficiency and carbon emission standards are not being achieved - i.e. that there is a gap between as-built performance and design intent. Studies such as at the Elmtree Mews development suggest a significant discrepancy can exist between the design and actual performance of both building fabric and services.

The GHA and partners developed a monitoring and testing programme with two main aims: 1) help close the gap between design aspiration and as-built performance, and 2) improve the processes for undertaking Building Performance Evaluation (BPE).

The GHA Monitoring Programme was set up in two phases, running from October 2009 through March 2013: Phase 1, **Post-Construction** Evaluation, measuring the performance of building fabric post-construction on a series of new-build residential projects, across a range of construction types; and Phase 2, **Post-Occupation** Evaluation, collecting in-use performance data from these houses in terms of energy and water consumption and Indoor Air Quality (IAQ), the performance of installed building services, and occupant behaviour/ perceptions.

This document focuses on the key results of the Post-Occupation evaluation and compares the findings. Detailed Post-Construction results can be found in the previously published, *GHA Monitoring Programme 2009-11: Technical Report.* Detailed Post-Occupation results are found in individual reports for each of the three evaluated developments (*Good Homes Alliance Monitoring Programme 2011-13: Technical reports: Derwenthorpe prototypes; One Brighton; Old Apple Store*).

Many issues were identified which affect the in-use performance in this programme. In particular, poor building services designs and installations. Additionally, from the difficulties encountered with the in-use monitoring, lessons have been learned to improve BPE in the hope that it can more easily be incorporated into the building procurement process.

2. Recommendations

Process

1. The benefits of Building Performance Evaluation (BPE) are highly significant. In all the projects that were the subject of monitoring the developers and professionals have learned about the realities of building and system performance. Building monitoring also helped identify several installation faults at each dwelling.
   BPE should be included as an integral part of the design and development process for new homes.
   This need not be to the extent of this programme – a reduced or 'lite' version could still be very effective and beneficial to the development team. It is important to assess the performance of the building and its systems at handover (prior to occupancy) as well as following a period of occupancy to increase certainty in the findings, and thus better target recommendations for improvement.
2. Fundamentally developers need to develop and implement a culture and formal process of learning and continuous improvement – but one which is based on learning from the realities of how their developments are performing, and to feed back this learning into the development process on an ongoing basis.
3. The design process for new housing developments needs further thought and investigation. The higher the level of innovation and system and fabric performance that is required, the greater the level and detail of design information needed. This requirement can conflict with such procurement methods as Design and Build, where aspects of the detailed design are left to the Design and Build contractor who may not be as knowledgeable as needed. In any event, where Design and Build is required, then much more consideration needs to be given to how to achieve building and system performance in reality within this contractual context.
   Industry players need to come forward with fully developed 'pattern book' solutions for new homes that encompass fully detailed designs and specifications based on fabric and systems that have been proven to perform. This approach will enable knowledge and learning to be incorporated within the pattern book. Procurement specialists should

assess how such initiatives could be included within, for example, Design and Build contracts.

4. It has proven much more challenging to get building systems to perform than was thought, and priority needs to be given to this given the extent of the performance gap in this area. A pan-industry group operating within the auspices of the GHA and its members, wider industry and academia is required.
5. The construction process for new housing requires a fundamental review of skill sets and knowledge with a shift of training emphasis to include knowledge of building and systems performance. Designers, specifiers and builders all need to become much more aware of the implications that defects or changes in specification have with regard to this aspect of buildings.
   Much more rigour is needed in terms of the application of a QA/QC approach to all stages of the development process and with a particular emphasis on construction.
6. All of this needs to be informed and addressed by significant training across all areas of the industry, including clients. A fundamental up-skilling of designers and construction teams is essential so that they become aware of and knowledgeable about the realities of building and system performance.
   Developers should engage an independent commissioning specialist to check and take measurements of building services (especially space heating, domestic hot water, and ventilation) on a random sample of dwellings in a new development (similar to air tightness compliance) to ensure conformance to both **Part F** & **L**. The installation of building services was a key **performance gap** area identified in this programme. Poor installations have significant energy consumption and occupant health consequences and greater oversight in this area is required.
7. A greater understanding is required with regard to the interface between the building and its systems and occupants. Occupants can have difficulty understanding new technologies and systems, with controls often too complex and/or entirely lacking any intuitive character.
   Energy savings from, for example, getting occupants to reduce standby loads, while still important, can be completely cancelled out by inefficiencies from poor services installations. The industry needs to stop blaming occupants for not operating systems in the most energy efficient way if the systems haven't been installed correctly. So while

interventions focussing on occupant consumption habits are important, developers should first look to improve areas they have more control and influence over: architectural design for in-use energy efficiency, building fabric and services design and construction, the selection of technologies, and **occupant handover**.
Much better and more developed handover processes and documents are required to ease this process, as well as the creation of new products and services which are more simple and intuitive to work and interact with.

Technology

8. Some technologies, such as centralised mechanical ventilation systems and communal heating systems, appear to be more susceptible to design and installation errors, and inefficient operation than other more traditionally used technologies. Part of this is of course their relative newness in the UK. However these 'performance gap prone' technologies are often more complex, especially when integrated into a system with other technologies. Larger schemes are often more vulnerable, with problems with these technologies magnified by greater scale.
   The incorporation of these technologies needs more care throughout all stages in procurement, from technology selection to occupant handover.
9. PV is a simple, near bolt-on technology and it should be considered for all new developments with a renewable energy requirement (without sacrificing good fabric and building services design). Photovoltaic (PV) panels were installed at each development, and analysis has shown that they produced very close to the anticipated amounts of electricity in each case. Comparing PV with other building integrated renewables, generally speaking PV requires less integration with other building services, does not add to the complexity of system controls, and is thus relatively easy to design and install. Operationally, it requires very little from building users, and if electricity is exported, there is not a technical issue with oversizing the array.
10. The requirement for mechanical ventilation and supply and extract flow rates should be reviewed in light of house usage and occupancy rates on an individual case by case basis. More sensitive, demand controlled ventilation systems should be investigated as possible solutions in projects.

11. For space heating systems with condensing gas boilers and wet distribution, a form of **compensation control** should be specified and installed as standard. This helps maximise the potential that a condensing boiler will actually be in condensing mode, and hence operating at a higher efficiency.

Guidance

12. Even with a 'fabric first' approach, SAP-driven targets for a development can lead to the selection of complex building services, often 'performance gap prone' technologies. This isn't necessarily wrong, but it needs to be recognised that these technologies require greater attention to detail.
    New guidance on the use of SAP from a performance gap perspective could prove a helpful navigational tool for developers and built environment professionals.
13. **Building Regulations Part F** and **CIBSE guides and Technical Memoranda** do not provide clear and consistent guidance in respect to overheating criteria, nor acceptable RH levels or CO_2 concentrations. Bands of acceptable or healthy concentrations or thresholds may be given, but these do not adequately factor in time in exceedance of these limits. Regulatory requirements and design guidance need to provide more sophisticated recommended tolerances.

Design

14. **Thermal mass** has the potential to help or hinder the control of high temperatures and if included needs a means of purging released heat, and therefore needs to be considered in a more nuanced way. Its inclusion need not require complex thermal modelling, but instead simple guidelines could be followed to prevent it from exacerbating possible overheating.
15. Local typologies need to be considered when assessing overheating risk. The inclusion of regional climate data is not enough – **urban density**, materials, air flow, and noise need to also be considered. For example, might street noise discourage occupants from opening windows to purge heat? (This was found at One Brighton).

16. When conducting BPE, as-built **SAP** inputs need to be examined against the actual as-built dwelling. Errors in as-built SAP calculations are common, and if SAP outputs are used as a yardstick in a BPE programme, mistakes can seriously skew any performance gap.
17. Considerably more care needs to be placed on the design, installation and operation of **centralised heating systems** (communal heating). The consequence of getting it wrong is not just insufficient heat provision, but also heat losses which can contribute to **overheating** and increase the carbon intensity of the system. Further, electrical loads from pumps and ancillary equipment can be very high, further weakening the argument that centralised systems are more efficient or less carbon intensive than individual systems. Design needs to consider not only efficiency, but also "**buildability**" and the management of the system, considering the necessary resource required to operate the system as intended in design.

Building management

18. Large developments, especially those trying to be innovative in sustainability, should consider establishing a part-time building manager role, such as the **Green Caretaker** at One Brighton. The focus of this role should be helping occupants to engage more effectively with new design features and technologies.

3. Introduction

Energy used in domestic housing in the UK is responsible for over one quarter of the UK's total carbon dioxide emissions[1]. In order to reduce carbon emissions in this sector, all new homes are required to meet **Building Regulations Part L1A (Conservation of Fuel and Power)**[2] (at the time of writing 2010 Building Regulations, with amendments made in 2013). This requires compliance with **SAP** 2009 (Standard Assessment Procedure)[3], which produces an energy efficiency design target. In addition, all homes in receipt of public funding are required to meet a specified **Code for Sustainable Homes** (CSH)[4] standard.

The Government has set ambitious targets for incremental changes to building regulatory standards, which are intended to achieve zero carbon new housing from 2016 onwards[5]. With the application of improved building fabric and building services measures, and the addition of low and zero carbon renewable energy generation, this is theoretically possible – housing developments have indeed been built which were designed to be very low or zero carbon.

However many low or zero carbon solutions are at present untested in-use, and there is growing awareness within the housing industry that, in practice, even current energy efficiency and carbon emission standards are not being achieved - i.e. that there is a gap between as-built performance and design intent. There is concern that this **performance gap** has the potential to undermine zero carbon housing policy[6]. In the UK we know very little about the way homes perform after they have been completed, with the exception being air-tightness. Initial studies, such as Low Carbon Housing: Lessons from Elmtree Mews[7], suggest a significant discrepancy can exist between design and actual performance of both building fabric and services.

[1] The Energy Saving Trust. Fabric first**.** Focus on fabric and services improvements to increase energy performance in new homes. CE320, September 2010
[2] http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/approved
[3] https://www.gov.uk/standard-assessment-procedure
[4]. Code for Sustainable Homes Technical Guide. November 2010. DCLG ISBN 9781859463314
[3] HMS Treasury The Plan for Growth published by Department for Business Innovation and Skills, March 2011. Construction p121.
[6] Carbon Compliance: Setting An Appropriate Limit For Zero Carbon New Homes: Findings And Recommendations, Zero Carbon Hub February 2011.
[7] The Elm Tree Mews Project, Joseph Rowntree Foundation - Bell, M., Wingfield, J., Miles-Shenton, D. and Seavers, J. (2010) Low Carbon Housing: Lessons from Elm Tree Mews. Joseph Rowntree Foundation, York. ISBN: 978-1-85935-766-8 (pdf). [www.jrf.org.uk/publications]

Further research, for example by Wingfield et al[8] and Bell et al[9], showed many of the new homes in the sample they tested were not achieving their design energy and ventilation performance standards. This performance gap is likely to have implications on the achievement of carbon reduction, thermal comfort and affordable warmth objectives, and could impact the long term physical integrity of the building fabric. For instance missing insulation and high levels of air leakage could result in increased risk of damp and condensation which could hasten the deterioration of a property's fabric.

Most energy related regulatory requirements are based around energy design targets modelled using SAP. In practice, it is also used as a prediction and design tool by designers (although it is a compliance tool), and there are a number of inherent assumptions made when using SAP software. Inaccuracies in SAP inputs can greatly affect outputs - recent evidence indicates that serious input errors may be fairly widespread. A study in the application of SAP for new dwellings found errors in 56 out of 82 assessments (68%), and that when corrected, about 20% of the dwellings failed to meet the regulatory Target Emission Rate[10].

Ultimately, SAP and other modelling software can never provide evidence to both the regulator and the constructor of what level of performance has actually been achieved. Currently there are no requirements for proof that new homes have achieved their planned energy performance in reality.

It is clear there would be benefit for new build housing schemes to undergo some form of comprehensive Building Performance Evaluation (BPE) in order to evaluate and evidence whether they have achieved, in reality, their anticipated energy efficiency and carbon performance. Although learning and improvement through a BPE programme could offer a competitive advantage for a housing developer, it is not widely understood what methods of evaluation exist or the level of monitoring and testing required for a robust programme.

---

[8] Wingfield, J., Bell, M., Miles-Shenton, D., South, T & Lowe, R.J. (2007) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Final Report: Lessons From Stamford Brook - Understanding the Gap between Designed and Real Performance, PII Project CI39/3/663, Leeds Metropolitan University, Leeds

[9] Bell, M., Black, M., Davies, H., Partington, R., Ross, D., Pannell, R. And Adams, D. (2010) Carbon compliance for tomorrow's new homes: A review of the modelling tool and assumptions. - Topic 4: Closing the Gap Between Designed and Built Performance. Report number ZCHD130210, Zero Carbon Hub, London. [www.zerocarbonhub.org]

[10] Trinick, Elliott, Green Shepherd and Orme, 2009 EEPH / CLG Research into Compliance with Part L of the Building Regulations for New Homes – Phase 2 Main Report. Faber Maunsell, AECOM.

3.1. Good Homes Alliance programme

The GHA and partners developed a monitoring and testing programme with two main aims:

1. help close the gap between design aspiration and as-built performance
2. improve the processes for undertaking BPE

An initial study, funded by the Energy Saving Trust, investigated the scope of monitoring required and defined the approaches to be adopted for the GHA Monitoring Programme[11]. This was undertaken by the Good Homes Alliance and its partners Leeds Metropolitan University, Oxford Brookes University and University College London, and was completed in May 2009.

The scoping study team suggested that detailed performance monitoring should incorporate three approaches:

1. *Post-construction testing*: Collection and analysis of data to calculate the thermal efficiency of the building fabric.
2. *Monitoring in use*: Collection and analysis of in-use data about energy and water consumption, temperature and **Indoor Air Quality (IAQ)** in occupied dwellings, and the performance of installed building services.
3. *Post-occupancy evaluation (POE):* Analysis of user behaviour patterns, comfort and satisfaction levels and perceptions.

The GHA Monitoring Programme was therefore set up in two distinct phases to ensure all three study approaches were conducted:

Phase 1, Post-Construction Evaluation

Measure the performance of the building fabric on a series of new-build residential projects, across a range of construction types.

[11] GHA Monitoring Programme 2009 – Phase 0: Summary findings, methodology and next steps. GHA May 2009.

Phase 2, Post-Occupation Evaluation

Collect in-use performance data from these units (energy and water consumption, IAQ, the performance of installed building services) and occupant behaviour/ perceptions.

The programme ran from October 2009 to January 2013. Phase 1, Post-Construction testing started in January 2010 and was completed in July 2010. Phase 2 monitoring began in April 2011 and finished in April 2013. Note that due to difficulties with equipment and site access, the monitoring was not always concurrent at all three sites and thus although Phase 2 effectively ran for two years, two years worth of data was not collected for any site (one year for two sites and approximately six months for the other).

Table 1. GHA monitoring programme overview

Post-Construction monitoring • **Coheating tests** • **Thermography** • **In-situ U-value testing** • **Air pressure testing**	Jan 2010 – Jul 2010
Post-Occupation monitoring • **Environment conditions** • **Energy consumption** • **Building services monitoring** • **Occupant survey and interviews**	Apr 2011 – Jan 2013

While Post-Construction results are briefly reviewed here, this document focuses on the key results of the Post-Occupation evaluation. Detailed Post-Construction results can be found in the previously published, *GHA Monitoring Programme 2009-11: Technical Report.* Detailed Post-Occupation results are found in individual reports for each of the three evaluated developments (*Good Homes Alliance Monitoring Programme 201-13: Technical reports: Derwenthorpe prototypes; One Brighton; Old Apple Store*).

4. Domestic Building Performance Evaluation

There are a number of BPE methods which can be employed, each providing useful information with respect to Post-Construction and Post-Occupation performance of new homes. Some of these include:

Post-Construction

- Testing building fabric performance
- Examination of building services installation and commissioning

Post-Occupation

- In-use monitoring, examining energy and water consumption, indoor environmental conditions, and building systems' performance, including **Low and Zero Carbon (LZC) technologies**
- Occupant feedback through occupant surveys and interviews

Although still useful on their own, combining several Post-Construction and Post-Occupation evaluation methods is necessary to understand the overall performance and contextualise and disaggregate the recorded data. For example, the measurement of fabric performance is also helpful in subsequently understanding the performance of the dwellings in use – once a baseline has been established for the performance of the building fabric, it is then easier to eliminate this from any measured discrepancies in performance. Further, occupant surveys provide essential context for measured energy consumption and air quality.

4.1. Post-Construction Evaluation

If homes are only monitored in use, it is difficult to dissociate the effects that arise from occupant behaviour and usage patterns from the issues associated with the performance of the building fabric itself. It is therefore essential to also measure the performance of the building prior to occupancy, as this establishes the building performance free from occupancy impacts.

Post-Construction performance evaluation techniques which were employed in this study are described below.

4.1.1. Coheating test[12]

A Coheating test is a method of measuring the fabric heat loss in an unoccupied dwelling. It involves heating the inside of a dwelling using electric heaters to a constant mean elevated internal temperature of around 25°C over a period of several weeks. By measuring the amount of electrical energy required to maintain the internal temperature each day, the daily heat input to the dwelling can be determined. The **heat loss coefficient** (W/K) for the dwelling can then be calculated by plotting the daily heat input against the daily difference between the inside and outside temperatures of the dwelling. The Coheating test is designed only to measure the heat loss through the fabric of a building.

4.1.2. In-situ U-value measurement

The insulative performance of building elements, such as a wall or a roof, can be measured using local **heat flux sensors**. These measure direct heat flow through various elements of the building fabric. The measurements are used to determine an effective average **U-value** for each element concerned, and the information can be used to quantify areas of heat loss from a dwelling.

4.1.3. Thermal imaging

Thermal imaging is a non-invasive, qualitative means of observing and diagnosing the condition of dwellings through temperature differentials. It can be used to check for high heat loss paths in dwellings. It can also assist in identifying building features that create **thermal bridges**, to check or prove insulation continuity, and to identify hidden sources of air leakage. If remedial works have been made to the fabric of a dwelling subsequent to problems being diagnosed, thermal imaging can be used to evaluate and verify improvements.

[12] Johnston, Miles-Shenton, Farmer, Wingfield. Whole House Heat Loss Test Method (Coheating). Leeds Metropolitan University, CeBE, June 2013 [http://www.leedsmet.ac.uk/as/cebe/projects/cebe_coheating_test_method_june2013.pdf]

4.1.4. Air leakage tests (air permeability/ airtightness test)

Air leakage is the uncontrolled flow of air through gaps and cracks in the fabric of a building, sometimes referred to as infiltration or draughts[13]. It should not be confused with controlled ventilation, which is the flow of air into and out of the building through purpose built ventilators, required for the comfort and health of occupants.

Blower door testing is a well-established technique and a pressurisation test forms part of building regulations compliance. The blower door test can be used in several ways:

- Assessing the air permeability of the building, (the air leakage from the whole envelope area of the building).
- Identifying air leakage points, which will allow for targeted remedial measures such as sealing.
- Measuring the effectiveness of remedial sealing

During an air pressure test, while the fan is pressurising or depressurising the dwelling, hand-held smoke pens can be used to find air leakage points. Thermal imaging can also be used during an air pressure test to help identify points of infiltration.

4.2. Post-Occupation Evaluation

Post-Occupation Evaluation involves monitoring dwellings in-use. Post-Occupation performance evaluation methods and focal areas used in this study are described below. These methods can help to determine how the key features of the new designs (enhanced airtightness, improved fabric insulation levels, renewable sources of energy) contribute to energy performance and ultimately to a home's overall carbon budget[14].

4.2.1. Energy and water consumption monitoring

Although recording total consumption of energy and water is useful, especially for statistical studies, to characterise energy and water performance some degree of submetering with frequent measurement should also be employed. In this study submetering has been used to divide energy consumption into end-uses, such as space heating, hot water, and fan usage.

[13] The Energy Saving Trust. Achieving air tightness in new dwellings. CE248 (2007)
[14] The Energy Saving Trust. (2008). CE298 Monitoring energy and carbon performance in new homes.

With this data energy consumption can be apportioned to pinpoint underperforming technologies or identify areas which demand further investigation. Energy use profiles were also created to characterise the energy demand of equipment over a day – this can help highlight unexpected usage.

4.2.2. Indoor environmental conditions monitoring

New dwellings should provide comfortable and healthy living conditions to occupants. Monitoring environmental conditions is key to understanding whether building services systems are delivering this, and can improve understanding of occupant behaviour and energy consumption.

Indoor temperature is important to monitor, examining incidences of under and overheating. The criteria used in the GHA study for overheating is provided below in Table 2.1 (adapted from **CIBSE** Guide A and CIBSE TM36 2005).

Table 2. High temperature comfort and overheating threshold degrees

Area	**Overheating** threshold [°C]	Comfort Threshold [°C]
Bedroom	25	23
Living room	28	26

Indoor Relative Humidity (RH) is another important factor to monitor as RH impacts occupant health and comfort, but also fabric health, and is an indicator for the effectiveness of the ventilation system. In the GHA study between 40-70% RH was considered as within the acceptable range.

CO_2 concentration is also often used as an indicator for IAQ. While industry guidance is not very clear, generally for the GHA study the following CO_2 thresholds were used (adapted from CIBSE Guide B, 2008):

Table 3. CO_2 concentration and IAQ indication

CO_2 concentration	*Indication*
Background level – 800 ppm	Good
800 – 1000 ppm	Adequate
>1500 ppm	Poor

Concentrations of other pollutants such as formaldehyde and **Volatile Organic Compounds (VOCs)** can also be monitored, though these were not included in the GHA study.

4.2.3. Building services monitoring

Correlating measured energy demand of specific technologies with environmental conditions, such as external temperature or **solar insolation**, can help determine the actual efficiency of installed building services equipment. Calculated efficiency can then be compared to manufacturers' and designers' claims and assumptions. This can help identify well or poorly performing equipment, highlight installation faults and determine the applicability of certain technologies.

4.2.4. Occupant survey and interviews

Occupant behaviour, dwelling usage patterns, and occupant interaction with their dwellings and building services (including heating and hot water systems, lighting, ventilation and appliances), has a significant effect on the energy efficiency and carbon emissions arising from dwellings.[15] To capture occupant perceptions the standardised **Building Use Studies (BUS) survey**[16] was used. This survey also enables benchmarking against other developments. Interviews and occupant walkthroughs are also crucial to better understand occupant behaviour and perceptions.

[15] Gill, Z.M., Tierney, M.J., Pegg, I.M., Allan, N. (2010),). Low-Energy Dwellings: The Contribution Of Behaviours To Actual Performance, Building Research and Information, vol. 38 (5), pp. 491-508

[16] http://www.busmethodology.org.uk/history/

5. Evaluated Housing Developments

The evaluated dwellings in this programme are from the following developments: Derwenthorpe, York; One Brighton, Brighton; and Old Apple Store, rural Somerset. The locations of the specific dwellings tested and monitored in this programme have not been identified to preserve the anonymity of the occupants.

Monitoring at Derwenthorpe was undertaken by the Centre for the Built Environment (CeBE), Leeds Metropolitan University, while One Brighton monitoring was undertaken by University College London, and Old Apple Store monitoring was conducted by Oxford Brookes University.

5.1. Derwenthorpe

Two dwellings on this site were evaluated. Derwenthorpe is located approximately 2.5km to the east of York. The dwellings are 2.5 storey, three bedroom detached houses developed by the Joseph Rowntree Housing Trust (JRHT). The dwellings were constructed between July and December 2009 as prototypes prior to the construction of the larger, 400 dwelling development.


Figure 1. Derwenthorpe prototype homes

House A was constructed using a **Structural Insulated Panel (SIPs)** build system. House B was constructed using **thin joint masonry** construction. Each dwelling was orientated North-West to South-East, with large glazed elements facing towards the South-East. Each dwelling has a sunspace designed to act as a thermal buffer in winter and to induce the **stack effect** in summer, to promote passive cooling. Windows are double glazed, argon-filled units.

The dwellings were designed so that high levels of fabric performance would be achieved. Airtight construction was coupled with a **Mechanical Ventilation with Heat Recovery (MVHR)** system, high levels of insulation were installed, and measures were undertaken during the design and construction process to minimise the amount of thermal bridging.

External walls were **parged** internally and then dry-lined with plasterboard on dabs. The ground floor comprised a suspended concrete slab with insulation placed below the slab, and the upper floors were constructed using timber I-beams. The roof is of a tiled pitched design.

Some electrical power is supplied to the dwellings by roof-mounted PV tiles. To minimise energy demand, the supplied electrical appliances are A- rated (washing machine, dishwasher and fridge-freezer), and the light fittings are suitable for energy efficient bulbs. In the future the houses can be connected to the **district heating system** that will form part of the larger development, but currently heat and hot water is supplied from gas boilers.

Additional technologies include rainwater harvesting and low flush toilets. Each dwelling is designed to be a lifetime home. House B has a disability lift/ platform fitted.

Based on the performance of buildings at design stage, the dwellings are expected to have a **Dwelling Emission Rate** of 12.35 and 12.39 $kgCO_2/m^2/yr$, for dwellings A and B respectively, and achieve an overall SAP rating of B. They are also designed to meet Level 4 of the Code for Sustainable Homes.

5.2. One Brighton

One Brighton is a mixed use neighborhood jointly developed by Crest Nicholson and BioRegional Quintain. The project is promoted as one of the country's first environmentally and socially sustainable '**One Planet Living**' communities. The development offers a range of residential accommodation, community and commercial/office space and comprises 172 homes (eco-studios, 1-bed, 2-bed and 3-bed units), around 1,000 m^2 of community space, and approximately 1,200 m^2 of commercial/office space.

Figure 2. One Brighton

The apartments at One Brighton have been designed following a set of 10 key design principles based on the 10 One Planet Living Principles (Desai, 2010):

1. Zero Carbon: Reducing carbon dioxide emissions by optimising building energy demand and supplying from zero carbon and renewable resources
2. Zero Waste: Reducing waste arising, then reclaiming, recycling and recovering
3. Sustainable transport: Reducing the need to travel and providing sustainable alternatives to private car use
4. Sustainable and local materials: Materials chosen for buildings and infrastructure to give high performance in use with minimised impact in manufacture and delivery
5. Sustainable and local food: Consumption of local, seasonal and organic produce, with reduced amount of animal protein and packaging
6. Sustainable water: Reduced water demand with rain and waste water managed sustainably
7. Natural habitats and wildlife: Existing biodiversity conserved and opportunities taken to increase ecological value
8. Culture and heritage: Cultural heritage acknowledged and interpreted. Sense of place and identity engendered to contribute towards future heritage
9. Equity and fair trade: Create a sense of community. Provide accessible, inclusive and affordable facilities and services
10. Health and happiness: Promote health and wellbeing. Establish long-term management and support strategies

The apartment buildings consist of a concrete frame infilled with 240mm clay **Thermoplan blocks**, externally clad with 100mm wood fibre insulation and rendered – a two-layer, single skin load-bearing wall system. The Thermoplan block structure is honeycombed which achieves an enhanced insulative property compared to other blocks (lower U-values), and are laid with thin bedding joints of adhesive to produce an airtight structural wall, which is also vapour permeable. The resulting external wall has a designed U-value of 0.21 W/m^2K and the air tightness target was $5m^3h^{-1}m^{-2}$ @ 50 Pa. Windows are triple glazed, with designed U-values of 1.3 W/m^2K. Summer time temperatures were designed to be limited by orientation and shading, exposed **thermal mass** and **heat exchanger bypass** operation in the MVHR units.

A biomass boiler with back-up gas boiler supplies heat to a community heating network. A community trust **Energy Service Company (ESCo)** manages the heating network and **private electricity wire**. Roof mounted PV arrays on each block provide a small amount of onsite renewable generation. Imported electricity is provided from a '**green tariff**' electricity supply contract.

A Green Caretaker works onsite to help maintain the 10 One Planet principles, and works with the residents to ensure composting, recycling and allotment facilities operate smoothly.

One Brighton was designed with the following in-use energy targets:

- Space heating demands < 30 kWh/m^2/annum
- Hot water < 45 kWh/m^2/annum
- Electrical consumption < 45 kWh/m^2/annum

5.3. Old Apple Store

Old Apple Store is a small development of 6 dwellings in a village to the east of Bridgwater in Somerset. The monitored property is a four bedroom, 139 m^2, detached house built in 2009 to Code for Sustainable Homes Level 5 (zero net carbon emissions from heating, hot water, ventilation and lighting). The construction method is timber frame filled with recycled paper insulation, with an outer layer of wood fibre board and clad externally in either softwood or lime render. The walls are dry-lined internally with plasterboard on battens. The ground floor is comprised of a reinforced concrete slab with insulation placed below the slab, and the upper floor was constructed using timber I-beams. The roof is a **mono-pitched** timber I-beam design. The windows are triple glazed, argon-filled units.

Figure 3. West elevation of monitored house

It is fitted with centralised **Mechanical Extract Ventilation (MEV)** to draw air continuously out of the house at a controlled rate. A passive solar strategy is used, with extensive glazing to the rear elevation protected from high summer sun angles by a large roof overhang and a first floor balcony. This glazing extends onto the living room/dining room and a small 'snug', both of which have hard tiled concrete floors to provide thermal mass storage and smooth passive solar gain to these spaces.

The house is fitted with solar hot water panels, and PV panels on the roof. Mains cold water is supplemented by harvested rainwater for toilet flushing. It is heated by a wood pellet burner in the living room with a back boiler feeding small radiators in each room.

Two houses of the same design were built; one house with rear aspect facing south as intended in the design, and the other with the rear aspect facing west. The former house was used for the Coheating test before sale in March 2010 but the subsequent buyers were unwilling for full Post-Occupation evaluation to be carried out - the latter house was used instead. Monitoring kit was installed in February and March 2011 and monitoring continued until June 2012.

6. Post-Construction Evaluation Results

This section provides an overview of the Post-Construction results conducted in 2010 and has been included in this report to provide greater context for the Post-Occupation results. Further detail can be found in the *GHA Monitoring Programme 2009-11: Technical Report.* Please note that in this section the following dwelling identification is applied:

Dwelling 1	*Joseph Rowntree Housing Trust, House B, Derwenthorpe*
Dwelling 2	*Joseph Rowntree Housing Trust, House A, Derwenthorpe*
Dwelling 3	*Ecos Homes, Old Apple Store*
Dwelling 4	*Bioregional Quintain, One Brighton*

A comparison between the measured **whole house heat loss** from the individual Coheating tests and the predicted whole house heat loss of all of the dwellings tested is shown in Figure 4 below.

The results show a performance gap between the measured and predicted whole house heat loss for almost all of the dwellings, with the size of the gap varying somewhat.

It is important to note that the predicted heat loss for these dwellings was already fairly small, particularly for Dwelling 4, so the difference between measured and predicted heat loss is actually a small number in absolute terms.

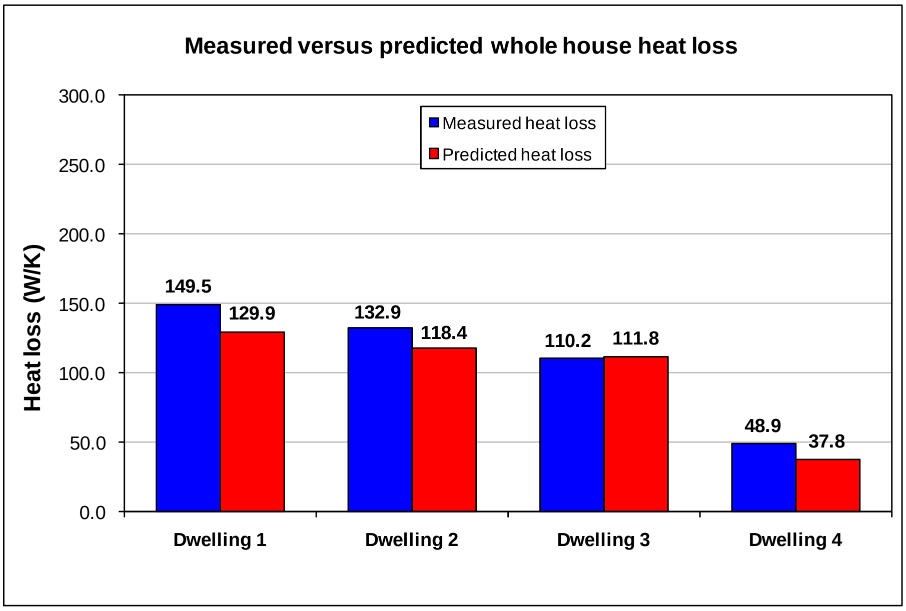

Figure 4. A comparison between the total measured whole house heat loss and the predicted whole house heat loss of the GHA-tested dwellings [Johnston, D., 2011[17]]

It also should be noted any performance gap identified between predicted and actual performance is dependent on the assumptions and accuracy of the predictions as well as the measured actual performance. Inappropriate design assumptions used in performance prediction modelling could result in overly optimistic or pessimistic predictions, and so in turn could influence a positive or negative performance gap. This is likely to have been the case for Dwelling 3, with the predicted heat loss higher than it should have been[18]. Thus the measured heat loss should not have been lower than the predicted heat loss. In relation to both Figures 4 and 5, the result for Dwelling 3 should be viewed with a degree of scepticism.

As whole house heat loss is very dependent on dwelling size and built form, a comparison of the **Heat Loss Parameter (HLP)** for each dwelling can sometimes be more useful (although this can favour some dwelling forms over others), shown in Figure 5 below. This better illustrates that the test properties varied considerably in terms of their discrepancy between predicted and measured HLP.

---

[17] Johnston, D (2011), Private report to Good Homes Alliance.

[18] According to Leeds Metropolitan University in the report to the GHA (see above), the predicted heat loss coefficient used in this analysis was overly pessimistic, as it adopted a y-value of 0.08 W/m^2K when 0.03 W/m^2K would have been more appropriate.

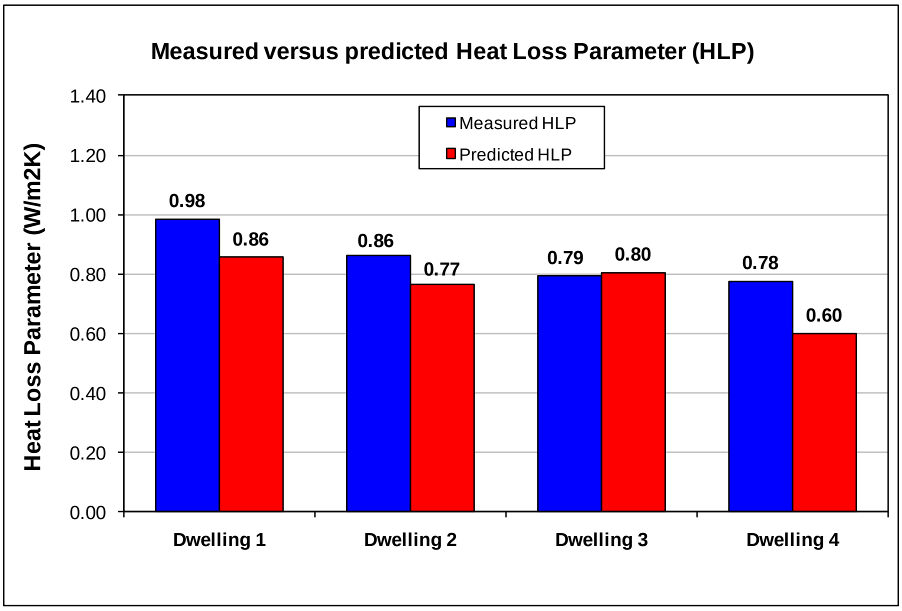

Figure 5. Measured versus Predicted Heat Loss Parameter for the GHA-tested dwellings. [Johnston, D., 2011[17]].

The results from the test properties are in line with research carried out by Bell et al[7] (see Figure 6). In their sample of 15 new homes built to various standards (including EcoHomes and the Code for Sustainable Homes levels, and under different Building Regulations), they found a gap between predicted and measured heat loss in the sample of homes they tested.

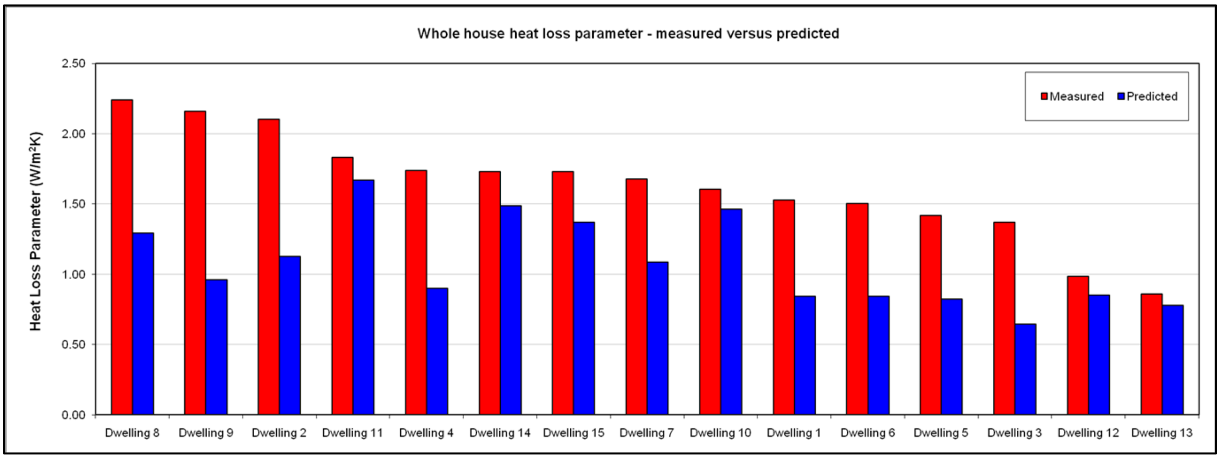

Figure 6. Difference in Whole House Heat loss, measured versus predicted. **Note GHA tested homes are not included**.

Thus, although a gap was identified in this programme, the percentage difference between predicted and measured performance of the GHA-tested homes was very good, i.e. low, when compared to the performance gap of the vast majority of the other tested homes. All of the GHA-tested homes had a gap between predicted and measured heat loss of less than 30%, whereas Bell et al reported that the gap between predicted and measured heat loss of the homes they tested can be over 100% (see Figure 7).

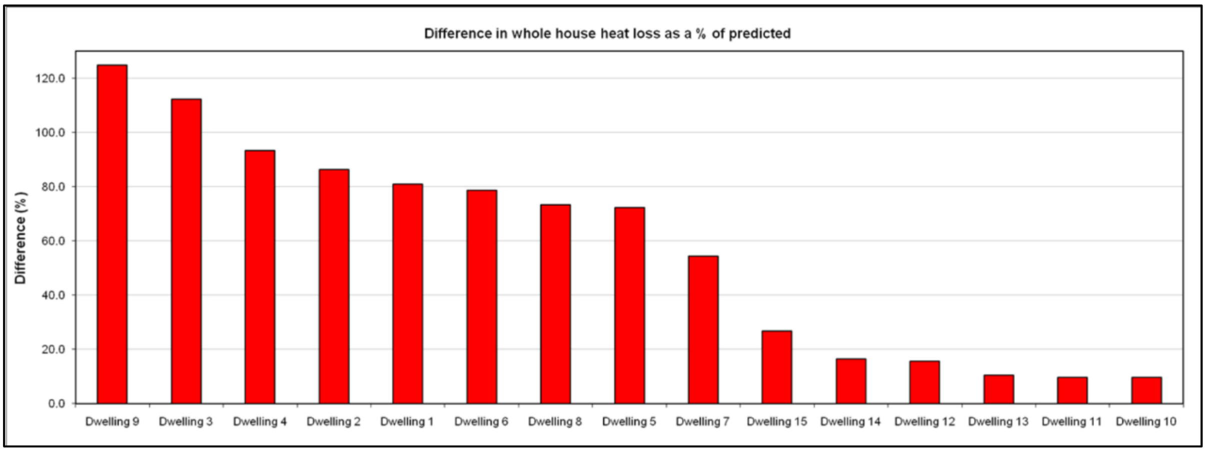

Figure 7. Difference in Whole House Heat loss as a % of predicted[7]. **Note GHA tested homes are not included.**

There are many potential reasons for the gap found between measured and predicted fabric performance. The team at Leeds Metropolitan University have identified several examples of common heat loss problems[6], including:

- insulation missing at door base, lintels, or junctions
- thermal bridges where internal structural joists are connected with external fabric or where frames are connected for balconies or the roof
- air leakage through penetrations and around windows and doors

In addition, some of the gap in performance could be due to the tests themselves. Current fabric testing methodologies are still at an early stage of development and there are therefore various degrees of uncertainty attached to each of the test results. In particular, the Coheating test had never been used before in the UK to test the whole house heat loss for an apartment (Dwelling 4, One Brighton study).

In this programme potential causes of discrepancy between measured and predicted building fabric performance was not investigated further. However in future BPE programmes it is recommended that this be done - to facilitate improvement in design and construction, reasons for underperformance must be identified.

7. Post-Occupation Evaluation Results: Derwenthorpe

For the detailed report please see *Good Homes Alliance Monitoring Programme 2011-13: Technical report: Derwenthorpe prototypes. Results from Phase 2: Post-Occupation Evaluation*.

7.1. Background

House A (SIPS construction) remained largely unoccupied from completion until temporary occupation during June 2012. The dwelling acted as a show home for the development and on occasions provided meeting space for JRHT. The data collected therefore provides a case study of **baseload** requirements for an empty dwelling. For this house, data between December 2011 and May 2012 (inclusive) was analysed for the report, as this proved to be the most comprehensive.

House B was occupied during the monitoring period, however obtaining data proved to be considerably more problematic, as occupants unplugged the datalogger and the CO_2 sensors, and the monitoring team experienced some equipment failure. This resulted in sporadic and inconsistent energy use data gathered between December 2011 and May 2012, and therefore energy data during this period has not been included in this analysis. Thus the monitoring period reported for House B is from October 2012 through March 2013 for energy data (incorporating most of a heating season), and December 2011 through May 2012, plus October 2012 through March 2013 for environmental conditions data.

Sensors measuring temperature, RH and CO_2 were installed to monitor the internal environmental conditions. Energy meters were installed on each ring main, at the fuse box. This enabled the demands for electricity to be described by its end use (e.g. lighting, cooking, and appliances).

Heat meters were used to determine heat supplied by the boiler to hot water and space heating. Cold water flow meters were also installed to measure cold water usage and determine the volume of hot water used within the dwelling. The electrical power output from the roof-mounted PV slates were monitored both before (DC power) and after the inverter (AC power) to measure its efficiency. A cold water meter was also installed to measure the harvested rainwater feed into the house.

4 in-duct thermocouples measuring MVHR system temperatures were installed to monitor heat recovery efficiency.

An external weather station was also installed to measure external climatic conditions, which included air temperature, RH, rainfall, wind speed and solar insolation.

Occupant surveys and interviews were attempted but were not successful in this study.

7.2. Key findings

7.2.1. Performance Gap

- Monitoring over the additional period for House B has enabled the comparison of the dwellings. The main finding is the significant difference between the electrical appliance usage of the two dwellings. House B is in the top quartile of UK consumption. The reasons for this very high usage is not known, but from observations undertaken during visits to the dwelling, it appears that it may be attributable to the very high number of appliances that are plugged-in and left on standby in the living room.
- The considerable energy consumption associated with appliances in House B highlights the importance of affecting change in household behaviour.

7.2.2. Building Services

- System energy demands and renewable energy generation appear to be similar for each dwelling based on the limited data available. The PV system provided sufficient energy to power the baseload demand of the dwelling's integral building services systems.
- Monitoring revealed complex interactions between system performance and environmental conditions. As the temperature difference between the exterior and interior increases, boiler efficiency rises, but the efficiency of the MVHR heat exchanger decreases. Higher solar insolation (often corresponding with temperature increases) lowers PV panel efficiency but the increase in DC output results in greater inverter efficiency.

- It appears that the **summer bypass** had not been activated on either MVHR system. This may have led to overheating if higher summer temperatures were observed.
- The MVHR duct flow measurement results undertaken by the research team indicate that there are discrepancies between what has been measured by the research team and the data contained within the commissioning certificates. This suggests that such systems are not being correctly commissioned.

7.2.3. Occupant health and comfort

- Master bedroom mean temperature was frequently above the living room in each dwelling and more prone to exceeding overheating thresholds; this could be a result of the south facing balcony glazing maximising solar gain in the bedroom, whereas the sunspace adjacent to the living room served as a thermal buffer.

7.2.4. Building Performance Evaluation

- Monitoring highlighted the inadequate sensitivity of the thermocouples measuring duct temperatures. The extracted air (pre heat exchanger) and supply air (post heat exchanger) temperatures were occasionally within the tolerances of the thermocouples. This resulted in some supply temperature measurements exceeding extract measurements, resulting in monitored heat exchanger efficiencies of over 100%.
- This study suffered as a result of data loss caused by occupants unplugging monitoring equipment. This highlights a common risk with these studies, but also emphasises the need to ensure the occupant fully understands what is required from them for the study (although this was done) and potentially developing monitoring equipment less vulnerable to occupant interference.
- The incorrect commissioning of the MVHR might not have been noticed if not for this research project - this could have resulted in poor IAQ.

8. Post-Occupation Evaluation Results: One Brighton

For the detailed report please see *Good Homes Alliance Monitoring Programme 2011-13: Technical report: One Brighton. Results from Phase 2: Post-Occupation Evaluation*.

8.1. Background

The apartment being monitored is situated on an intermediate floor of One Brighton. The apartment is occupied by a woman in her 30's, who commutes out of Brighton and is therefore out of her home most of the day, Monday to Friday. The participating apartment in the Post-Occupation study is not the same apartment that was fabric tested.

This study examined energy and water consumption, indoor environmental conditions, and occupant perceptions. Monitoring equipment was installed in October 2011. 4 electrical submeters were installed to measure energy demand from the MVHR, sockets, lighting, and cooker. Additionally a heat meter was installed to measure space heating demand. Submetered energy was correlated against total electricity and heat data provided by the ESCo.

Indoor environmental parameters monitored were temperature, relative humidity and CO_2 levels in living room and bedroom. A weather station recorded: temperature (^oC) and RH, wind speed (m/s) and wind direction, rainfall (mm), barometric pressure (hPa), and solar radiation (W/m^2).

A 'walkthrough' and in-depth interviews with occupants were conducted, in addition to two site wide occupant surveys: the standardised BUS, and a separate survey designed to enable quantification and apportionment of building performance to occupant behaviour.

Under this programme, data from November 2011 through October 2012 for the One Brighton flat was analysed. However evaluation work at One Brighton is also being funded under the Technology Strategy Board's Building Performance Evaluation programme. Under this, additional parameters were analysed in four more apartments. Thermocouples were fitted measuring ventilation duct air temperature in addition to window sensors to better understand and characterise the ventilation system operation in conjunction with occupant use of the windows for fresh air and to control indoor temperatures. Biomass consumption and PV generation was also analysed. These results will be made available in a separate case study.

8.2. Key findings

8.2.1. Performance Gap

- Compared against heat energy benchmarks, One Brighton appears to perform well. The main note of caution here is around the effect of heat losses from the communal heating system, which are significant. Thus this is validation of the building fabric in reducing heat demand, rather than communal heating system in efficient heat delivery.
- Actual electricity consumption of the apartment was slightly lower than the target of the One Brighton average and close to the UK stock average.
- Electricity used by the MVHR is proportionally high. It equates to approx 30% of the overall electricity consumed in the apartment, reaching almost 40% in summer.

8.2.2. Building services

- As expected, electricity consumed for lighting is higher during winter months. However, electricity used in the MVHR seems to increase in summer months (40% of the overall electricity used in summer compared with 27% during winter). An initial explanation for this is that the system may have been used at a higher fan speed to reduce the internal temperatures during warm days.
- Significant internal heat gains came from heat distribution systems. These caused raised temperatures in circulation spaces. Additional heat gains came from uninsulated components of the **Heat Interface Units (HIUs)** within apartments.
- The MVHR system presented challenges in design and installation. Designers responded to the lack of space in the apartments by placing the MVHR above the ceiling in the bathroom. This severely limits access for maintenance and replacement of filters, and may in the longer term affect IAQ and operational life of the system.
- Quality commissioning of systems such as the MVHR units is essential in a project like One Brighton. In this case the MVHR was not installed or commissioned as recommended by the manufacturer. In addition to poor ducting affecting air flow rates, the heat

exchanger bypass does not appear to be working. Commissioning documentation found during the evaluation was limited to a simple physical record of its installation in each apartment.

8.2.3. Occupant health and comfort

- The wall construction at One Brighton is designed to be intrinsically airtight and free from thermal bridges and convective bypasses. Infra-red images taken both from the outside and the inside the building and measurements made during the Coheating test are all consistent with this. The '*High thermal performance standards'* considered for insulation (40% above 2002 building regulation), windows (U-value of 1.3 W/m^2K), and air tightness targets ($5m^3h^{-1}m^{-2}$ @ 50 Pa) were lower than required under the **Building Regulations (ADL1A** 2006), which plays a key role for providing comfortable conditions during cold months.
- Heat use is dominated by the use of hot water. Despite low space heating usage, recorded internal temperatures in the apartment during cold months were above comfort levels (between 19^oC and 25^oC) most of the time. This demonstrates that the building fabric is providing good thermal insulation.
- There is clear evidence of a tendency to overheat at One Brighton. Primary determinants of overheating are solar heat gains through fabric and fenestration, fabric heat transfer and thermal mass, ventilation and the control of internal heat gains. The work and measurements described in this report took place during a year in which maximum external temperatures in summer were around 2°C lower than in the heat wave of August 2003. In the event of a similar, or of an even more severe heat wave in the future, conditions at One Brighton could become severely testing.
- Parts of the One Brighton development are shaded, but parts are exposed to significant levels of solar radiation, especially apartments facing South-East overlooking Fleet Street. In the latter, external shading, or window systems (such as 2+1 glazing) that incorporate effective protection against solar gain, would have been beneficial in reducing heat gain and overheating.

8.2.4. Occupant handover

- External noise from busy streets appears to be a factor that limits window opening in hot weather. A tendency not to open windows in hot weather may have been reinforced at One Brighton by the residents manual provided by the developer that states:

  "keeping windows closed in summer will allow your (MVHR) unit to provide free cooling by letting in cooler air from outside and extracting warmer air from inside your home".

- Some residents had the expectation that the ventilation system also functions as a cooling system. This points to a failure in the occupant handover procedure. Confusion on the part of occupants about the function of the MVHR system in summer is likely to lead to disappointment.

9. Post-Occupation Evaluation Results: Old Apple Store

For the detailed report please see *Good Homes Alliance Monitoring Programme 2011-13: Technical report: Old Apple Store. Results from Phase 2: Post-Occupation Evaluation*.

9.1. Background

As previously stated, the house monitored for the Post-Occupation Evaluation was not the same house as was Post-Construction tested, but of the same design and construction.

The occupiers were a semi-retired couple with an interest in green issues. Their occupancy patterns were fairly constant during daytime and evenings, with increased occupancy mainly during school holiday periods with family visiting.

This study examined energy and water consumption, the performance of LZC systems, indoor environmental conditions, and occupant perceptions. Monitoring kit was installed in February/March 2011 and monitoring continued until June 2012. The reported period for energy use was from June 2011 through May 2012, and for environmental conditions from March 2011 through February 2012.

Energy consumption was monitored with various submeters. Electrical submeters were installed to measure energy demand from pumps (space heating, rainwater, solar), the central MEV fan, and the immersion heater. Heat meters were also installed to measure central space heating and hot water use. The intended heat meter on the solar hot water system could not be used as the installer pointed out that this would invalidate the warranty. Instead, a manually read kWh output meter was fitted by the installer, which required regular reading and recording of data by the householders. Exported electricity from the rooftop PV array was not monitored as the electricity provider was unwilling to change the main meter for a model that would allow pulse enabled metering of exported power. The householders were asked to keep a record of every sack used of wood pellets.

External conditions were also monitored, in addition to indoor temperature and RH in four rooms including living room, kitchen, master bedroom, and ground floor study, and CO_2 levels in the living room.

Occupant behaviour and satisfaction evaluation techniques were also used, including 2 BUS surveys, an interview, and a walkthrough survey. The results from these evaluation techniques were triangulated with monitoring and spot check measurements to produce a balanced view of occupant satisfaction and concerns.

9.2. Key findings

Although the house achieves Code for Sustainable Homes Level 5 requirements and generally performs better than energy design predictions, the occupants were not happy. The key reasons are identified as the mismanagement of handover, lack of pre-defined protocol for fine-tuning and repair of service systems, and missing attention to detail in construction finish and design layout.

9.2.1. Performance Gap

- The overall energy use is broadly in line with expectations given the nature of the house and the occupancy levels. However, measured primary heating energy use is lower than expected from the SAP calculation – this perhaps reflects the problems experienced with the central heating system and the under-heating experienced. The SAP calculation predicts primary space heating energy use of 5797 kWh per year, whereas 3283 kWh was recorded based upon wood pellet usage, or 57% of that predicted.
- Low hot water usage, lower than assumed internal temperatures and boiler setting, and conservative estimates of boiler and PV efficiency have led to measured energy consumption being less than the SAP predicted energy usage. Additionally the MEV fan energy consumption was not included in the SAP calculation. But SAP would not account for installation errors – it assumes that the central heating pump is switched on only during the heating season while in reality it was on throughout the year due to a commissioning fault.
- The full design intent was not met since the house was designed to be south facing while in reality it is west facing. Consequently the anticipated solar gains in the spring and winter are not received.
- Overall, the house meets the Code for Sustainable Homes Level 5 requirement regarding carbon neutral water heating, pumps and fan energy, assuming lighting uses less than 2.5kWh per day.

9.2.2. Building Services

- The house was experienced as being cool and hard to heat. The solar façade is west-facing rather than the optimal south orientation, and thus lacks the expected beneficial solar gains in the spring and winter. The wood pellet heating system with manual refuelling was not used as much as it might have been if refuelling was automatic. One consequence was that the immersion heater was used more than expected, especially during the '**shoulder**' seasonal periods when solar radiation is limited but there is little space heating demand, and thus the wood pellet boiler is not yet in use. Heating water using the immersion heater is the most carbon-intensive form of heating possible in this house.

- The low commissioned boiler flow temperature, continuous MEV and the undersized radiators contributed to unsatisfactory winter comfort levels. Consequently the measured heating energy use was less than expected. The boiler temperature setting can easily be adjusted to provide 50-70% higher heat output from the radiators.

- The need to manually feed the wood boiler made the system labour intensive and less likely to be used in the shoulder months (autumn and spring) for hot water production. Lack of designed storage for the wood pellets was a major issue. Movement and storage of 1 ton of pellets per house should have been resolved and integrated in the early stages of site and building level planning.

- There are some potential reductions to be made from the electrical baseload. The central heating pump was on continuously, leading to approximately an extra 245kWh of electricity being used.

- The need for a steady rate of mechanical extract ventilation should be investigated as the home was not occupied to its design expectation, and monitored RH levels were well within the comfort range of 50-65%.

- The rainwater harvesting system had initial fitting problems but proceeded to work effectively; occupants learned to maintain the filter system although this was not mentioned during the handover process. The system was found to supply approximately 69 m^3 of non-potable water for toilet flushing and washing machine. This equates to about half of typical usage for two occupants in a UK house.

- 40% of overall PV generation was during the months of June, July and August. The measured efficiency was 12.99% (including inverter losses) for the whole year. On average, the panels operated at about half the peak output in the summer.

- All pumps and fan electricity consumption was more than covered by the PV. The PV panels performed as expected, although it was not possible to measure the amount of electricity exported. The photovoltaic array supplied more than 50% of projected electricity usage and provided more energy than is obligatory for Code Level 5 minimum requirements. It did not have any maintenance or service problems, although the occupants would have liked more information on how to detect any problems.
- The solar hot water system was sized for a family of four and was underutilised because of the lower than planned occupancy, providing 48% of overall yearly hot water requirement, which is slightly less than the 50-60% often claimed.

9.2.3. Occupant health and comfort

- While overall summer temperature was satisfactory, overall winter temperature was rated as very unsatisfactory in the BUS survey. This was confirmed by monitoring results which showed that the average temperature from October to March 2012 was mostly between 15°C and 20°C.
- The occupants were pleased with the high ceilings on the upper floor and the extent of daylight received in most areas.
- The monitoring showed predominantly good air quality and the dust free environment played a role in controlling a related health condition of one of the occupants. On the other hand, the low winter temperature was perceived to cause health problems.
- The high thermal mass provided by the concrete tiled floors along with the good shading by the balcony controlled peak summer temperatures to mostly under 25°C.

9.2.4. Occupant satisfaction

- The occupants were happy with the design and visual appeal of the development but the poor quality of the material finishes and inadequate supervision (highlighted by windows being fitted inside out, poor layout of fittings in the bathroom, and leaks in WC) during the construction process had a large impact on satisfaction.
- The open plan layout with large windows and balconies was successful in creating a light internal environment.
- The difficult relationship between the occupants and the developers concerning delay in handover, quality of construction, repairing defects etc. overruled many positive aspects

of the development leading to an adverse impact on the **forgiveness factor** by the occupants.

9.2.5. Occupant handover

- Major misunderstandings like the purpose and type of ventilation system installed indicate large gaps in the occupant handover process.
- Timing of the occupant handover was inconvenient as it occurred while some construction was still on-going. Information provided was perceived as minimal with little information about the role of different equipment.
- The main occupant handover document, although containing relevant section headings, lacked user focused information on trouble shooting and maintenance. Some parts of the manual are in a foreign language. Occupants felt that they had to work out the operation of various systems themselves and correct defects with the help of local tradesmen.
- It would have been useful for the guide to have contained information on where to buy and fit spares (e.g. lighting), common problems, trouble shooting and maintenance instructions in clear, simple language.

10. Conclusions and Recommendations

The aims of the GHA programme are: 1) help close the gap between design aspiration and as-built performance, and 2) improve the processes for undertaking BPE.

Many issues were identified affecting the in-use performance in this programme, in particular poor building services designs and installations. Additionally, from the difficulties encountered with the in-use monitoring, lessons have been learned so that BPE can be improved in the hope that it can more easily be incorporated into the building procurement process.

Conclusions and recommendations listed below address both the programme's aims.

10.1. Indoor Air Quality and comfort

- Mixed results were found for IAQ (CO_2) across the developments. A low concentration of CO_2 was found at the Old Apple Store, which may be related to low occupancy, but high concentrations were found at One Brighton, where the ventilation system was poorly installed.
- RH levels were generally within healthy, comfortable range throughout the developments.
- At One Brighton a high incidence of overheating was found, compounded by a dysfunctional heat exchanger bypass on the MVHR unit, while at Old Apple Store potential under-heating was found, which was the result of inadequately functioning space heating system.
- Thermal mass has the potential to help or hinder the control of high temperatures and if included needs a means of purging heat, and therefore needs to be considered in a more nuanced way. Its inclusion need not require complex thermal modelling, but instead simple guidelines could be followed to prevent it from exacerbating possible overheating.

- Local typologies need to be considered when assessing overheating risk. The inclusion of regional climate data is not enough – urban density, materials, air flow, and noise need to also be considered. For example, might street noise discourage occupants from opening windows to purge heat? (This was found at One Brighton).
- Building Regulations Part F and CIBSE guides and Technical Memoranda do not provide clear and consistent guidance in respect to overheating criteria, nor acceptable RH levels or CO_2 concentrations. Bands of acceptable or healthy concentrations or thresholds may be given, but these do not adequately factor in time in exceedance of these limits. Regulatory requirements and design guidance need to provide more sophisticated recommended tolerances.

10.2. Energy consumption

- Different monitoring periods and submetering installations meant that a meaningful energy consumption comparison between the sites was unfortunately not possible.
- The success of the monitored dwellings in achieving their energy targets was mixed. At One Brighton, while the monitored flat did not achieve the electricity target set, over the entire development, average electricity consumption did better the design target of 45 $kWh/m^2/annum$. The heat demand target was also achieved in the flat and across the site. At the Old Apple Store the in-use carbon neutral regulated energy (CSH L5) was achieved.
- High electricity demand associated with consumer electronics, such as in the occupied house in the Derwenthorpe prototypes study, highlights the need to engage householders to reduce ‘unregulated’ electricity consumption.
- Orientation is pivotal to solar design and should be part of the design process from the start of the project. Designs need to factor in orientation on site and should not necessarily adhere to the same house design throughout a development regardless of orientation.
- Dwellings are increasingly being specified with systems to reduce energy consumption such as MVHR, solar thermal systems, even Building Management Systems in some new

dwellings. These systems frequently add higher carbon intensive electricity loads to save lower carbon intensive heat loads. However at the Old Apple Store and Derwenthorpe, the PV installed was sufficient to offset the energy from these electricity loads.

10.3. Building services

- This programme identified many problems with building services installations - as such it was very difficult to determine whether these technologies, assuming they have been installed correctly, are the most appropriate technologies to use to maintain healthy living conditions and save energy.
- Discrepancies were found between designed and measured flow rates for the MVHR systems at One Brighton and at Derwenthorpe discrepancies were found between flow rates on the actual commissioning certificates and what Leeds Metropolitan measured. The continuously running space heating distribution pump at the Old Apple Store further points to a breakdown in the quality of service provided by the commissioning engineers. The building services in these developments are not particularly complex compared to non-domestic services.
- Developers should commission an independent commissioning specialist to check and take measurements of building services (especially space heating, domestic hot water, and ventilation) on a random sample of dwellings in a new development (similar to air tightness compliance) to ensure conformance to both Part F & L. Note that Part L and F 2010 Regulations may go some way in do this, by providing more detailed checklists and commissioning sheets. The installation of building services was a key performance gap area identified in this programme. Poor installations have significant energy consumption and occupant health consequences and greater oversight in this area is required.
- The control of systems with multiple heat inputs needs to be more carefully considered. At the Old Apple Store, the design of the manual feed for the wood burner resulted in the carbon intensive electric immersion heater being used frequently in ‘shoulder’ months (where space heating was not necessarily required but solar thermal output was not yet high). Additionally, the electric immersion also required manual switching.

Automated control and operation might have improved the occupant's satisfaction with the hot water system and reduce the carbon footprint associated with domestic hot water production. However, increased control and automation brings with it more sophisticated commissioning requirements. Given the installation faults discovered during this evaluation, increased 'intelligence' in building services needs to be accompanied by a commensurate increased intelligence in installation, or operational problems found could be compounded and efficiency gains unrealised.

- No boilers in this study incorporated compensation features. The commissioned flow temperature was too low at Old Apple Store and in Derwenthorpe a clear relationship was established between boiler efficiency and air temperature difference (and thus flow and return temperature difference). Compensation control (if this could be integrated with biomass boiler technology) could have potentially eliminated an underheating problem and helped maintain higher boiler efficiency. For space heating systems with condensing gas boilers and wet distribution, a form of **compensation control** should be specified and installed as standard. This helps maximise the potential that a condensing boiler will actually be in condensing mode, and hence operating at a higher efficiency.

- Building occupation can differ greatly from designed, and the number of bedrooms is the primary determinant for the design of ventilation rates in mechanically ventilated homes (in adherence to Part F), not the anticipated occupancy. At the Old Apple Store, which had lower than designed occupation, the ventilation rate was potentially too high, resulting in unnecessary heat loss.
  With the exception of boosted modes, the mechanically ventilated systems evaluated are not sensitive to actual occupation. Thus in highly occupied dwellings they have the potential to under-ventilate or frequently operate in boosted mode, possibly resulting in poor health conditions or a higher fan energy consumption. In lower occupation dwellings, over-ventilated dwellings can lose more heat and consume more fan power than is necessary (as in the Old Apple Store).
  The requirement for mechanical ventilation and supply and extract flow rates should be reviewed in light of house usage and occupancy rates on an individual case by case basis. More sensitive, demand controlled ventilation systems should be investigated as possible solutions in projects.

- Although emphasis is rightly placed on occupant education in terms of reducing energy consumption and the operation of building services such as heating and ventilation systems, unless the services have been effectively designed and installed correctly, this can be a somewhat futile and frustrating exercise. Energy savings from, for example, getting occupants to reduce standby loads, while still important, can be completely cancelled out by inefficiencies in poor services installations, such as at Old Apple Store where the space heating distribution pump continuously ran out of heating hours.
  The ventilation system at One Brighton is also case in point – the occupants may be taught how to use MVHR systems to maximise their effectiveness (changing filters, fan speed settings, etc) but ultimately without substantial changes to the design, installation and controls to the systems at One Brighton, improvements in operation will only go so far. The industry needs to stop blaming occupants for not operating systems in the most energy efficient way if the systems haven't been installed correctly.
  So while interventions focusing on occupant consumption habits are important, developers should first look to improve areas they have more control and influence over: architectural design for in-use energy efficiency, building fabric and services design and construction, the selection of technologies, and occupant handover.

- PV has generally met design expectations in all locations. For houses, a modestly sized PV array can offset electricity consumption (kWh) associated with modern building services in low energy homes, i.e. fans, pumps, and low energy lighting. PV is a simple, near bolt-on technology and it should be considered for all new developments with a renewable energy requirement (without sacrificing good fabric and building services design). Comparing PV with other building integrated renewables, generally speaking PV requires less integration with other building services, does not add to the complexity of system controls, and is thus relatively easy to design and install. Operationally, it requires very little from building users, and if electricity is exported, there is no a technical issue with oversizing the array.

- Considerably more care needs to be placed on the design, installation and operation of centralised heating systems. The consequence of getting it wrong is not just insufficient heat provision, but also heat losses which can contribute to overheating and increase the carbon intensity of the system. Further, electrical loads from pumps and ancillary equipment can be very high, further weakening the argument that centralised systems are more efficient or less carbon intensive than individual systems. Design needs to consider not only efficiency, but also “**buildability**” and the management of the system, considering the necessary resource required to operate the system as intended in design.

- For new technologies, or technologies found to be performance gap-prone, special care is required. It is recommended for each project potential pitfalls are identified and addressed at each procurement stage.
- Training and improved understanding of building services is required at all levels of the supply chain to improve in-use energy and health related outcomes. Developers need to understand performance gap issues and learn how they might improve the performance of their developments through a procurement process that could lead to a better outcome. For example, Employer’s Requirements can be improved by providing more performance requirements for the building fabric and services. Further, project team selection needs to factor in more than cost – quality, ability and experience with technologies also need to be considered.
  Designers need training to understand factors that affect “buildability” and the operation of building services in their designs, product selections or performance requirements. During construction, contractors need training to understand operational principles of the services better, best practice and the in-use implications for poor installations. Most importantly though, greater oversight is required to make sure systems are installed correctly and personnel are given the time they need to install the system correctly – the cost-implication of which developers and contractors can discuss given they both have received performance gap training and are in the same frame of mind about the issue.
  As the energy-efficient operation of many systems depends on the occupants, they too need training. This should occur during the second stage of the occupant handover. Finally, repair and maintenance tradesmen need training as many developments are installing complex and bespoke building services systems.

10.4. Occupant handover and engagement

- The occupant handover process and documentation should be more thorough and user friendly. At the Old Apple Store, the negative impacts of the hasty handover conducted at a stressful time when the occupants were moving in suggests that instead of just one walkthrough as part of the occupant handover, there should be two. The first should be just after they move in, when all materials such as guides and manuals are presented, and all services are demonstrated. The second walkthrough should take place a few months later, when the occupants have settled in, are less stressed, and have more questions after trying out the system themselves. Demonstrations at this time should focus more on how to operate the building for energy efficiency, comfort, health and safety.
- At One Brighton, occupants misunderstood the MVHR functionality, believing that it provided cooling (in one document it states that the MVHR provides 'free-cooling', a building services term most people probably do not understand). Clearly written and demonstrated information on the function and maintenance of all service systems is essential for all energy efficient homes. As with the demonstrations, handover documents need to provide operational guidance taking energy efficiency, comfort, health and safety into consideration.
- Large developments, especially those trying to be innovative in sustainability, should consider establishing a part-time building manager role, such as the Green Caretaker at One Brighton. The focus of this role should be helping occupants to more effectively engage with new design features and technologies.

10.5. Building Performance Evaluation

- Building monitoring helped identify several problems with each dwelling, especially identifying poor services installation and commissioning, which came up in all three sites. For example, at Derwenthorpe improper MVHR system commissioning would not have been noticed if not for the presence of the research team, and this could have resulted in poor IAQ. At the Old Apple Store, the post-occupancy survey and monitoring detected an underheating problem and commissioning error in the space heating system. These installation faults may not have been detected without BPE, especially in regards to the MVHR system. Additionally, the impacts of less than optimum occupant handovers were detected in the occupant interviews. Without post-occupation engagement, it is unlikely these views would have been captured.

- A level of BPE should be included in all new developments. This need not be to the extent of this programme – a reduced or 'lite' version could potentially be very effective. However, a combination of post-construction and post-occupation testing is required to increase certainty in the findings, and thus better target recommendations for improvement. When implementing a BPE programme it is important to remember that its purpose is threefold:
    1. Identify potential problems during design and construction before they occur or are difficult to fix. Thus evaluation programmes ideally should begin during design stages.
    2. Identify problems with the development after completion or during occupation so that these can be remedied as far as possible.
    3. Learn from the evaluation programme to improve future projects.

- One focus of this programme was to measure IAQ and energy consumption – in some cases it was analysis of this data that pointed to faulty installation and operation of services. Examining the installations and reviewing the commissioning first could have potentially provided a shortcut. An essential part of BPE therefore needs to include a review of building services installations and a commissioning check. Part F &L 2010 go some way to address this by providing more detailed checklists and commissioning sheets. However random checks before Practical Completion could provide greater assurance services are being installed correctly.

- The accuracy of the design prediction will largely affect the discrepancy between design and as-built performance, exaggerating or underestimating a perceived gap. Before undertaking BPE testing, as-built SAP inputs need to be examined against the actual as-built dwelling. Errors in as-built SAP calculations are common, and if SAP outputs are used as a yardstick in a BPE programme, mistakes can seriously skew any performance gap. That is not to say original or early stage aspirations should be dismissed or not included in the evaluation, but reviewed in the context that as the building project developed, aspirations (such as intended efficiencies or technologies) may have slipped. Reviewing why this happened can be just as revealing as physical BPE testing.

- Design and construction documentation proved difficult to come by in some studies, as documents were simply missing or possibly were never completed. This impacted the lessons that could be drawn from this study and limited the comparison of design intentions with as-built performance. If developers want to improve their processes by learning through a BPE programme, documents need to be kept throughout the entire procurement process, especially SAP files (both SAP worksheets and Data Input Reports), M&E specifications, architectural details, and commissioning and testing sheets.

- The ultimate aim of BPE is to provide feedback to improve design and construction and occupant engagement processes. As such any developer (or built environment professional) wanting to institute a BPE programme needs to also examine their own organisation to determine how knowledge captured in the process could be most successfully embedded in their business.

Glossary

baseload power: similar to standby power, but its use in this document is distinct. Here baseload power represents the minimum, constant electrical power draw from essential systems and appliances such as ventilation fans, security systems, building services controls, and fridge/freezers.

buildability: also called constructability, in this document it refers to the extent to which the design of the building facilitates the ease of its construction, subject to its overall requirements (Construction Industry Research and Information Association definition).

blower door test: primarily used to measure the airtightness of buildings, A blower door primarily consists of a variable speed fan, pressure instrumentation, and a mounting system, which is used to place the unit into a doorway for the test.

building fabric: in this document, the components that make up the building structure, including load bearing walls, insulation, floors, windows and doors, etc.

building services: the utilities, including electricity, gas, heat, data, and water, supplied to a building, and then used to maintain the safety, health and comfort of building occupants. This document focuses on the following building services design areas: lighting, small power (appliance use), space heating, hot water, and ventilation.

Building Regulations Part F: **Approved Document F 2010** sets the current standards for ventilation in England and Wales.

Building Regulations Part L: **Approved Document L1A 2010**, with 2013 amendments, sets the current standards for the Conservation of Fuel and Power in New Dwellings in England and Wales.

centralised heating systems: also referred to as communal or district heating systems in this document, they differ from individual systems by removing heat production from a dwelling to a centralised plant room, where heat is then transported through a network into multiple dwellings on site.

Chartered Institution of Building Services Engineers (CIBSE): sets standards and provides best practice advice and criteria for building services engineering.

Code for Sustainable Homes (CSH): the national standard for sustainable design and construction of new homes. It rates the performance of a new home against nine categories of sustainability: energy/CO_2, water, materials, surface water runoff, waste, pollution, health and well-being, management, and ecology. Although voluntary, achieving certain levels is sometimes required by local planning policies and for affordable housing funding. Additionally, achieving level 3 for 'energy' is now required by Building Regulations Part L.

compensation control: for this document, a boiler control function that varies the flow temperature of the space heating fluid to maintain higher operating efficiency. Flow temperature is typically varied as a function of external temperature (weather compensation) or return temperature (load compensation).

Energy Service Company (ESCo): a business providing energy solutions, for this document primarily the operation, including maintenance and billing, of centralised heating systems and private wire electricity networks.

forgiveness factor: quantifies how occupants are willing to forgive perceived inadequacies of their environment because of their appreciation of other building qualities which increase their overall comfort or add to their experience of the building. For example, good internal finishes can give the building a high "forgiveness" factor in relation to comfort issues. The BUS quantifies the "forgiveness index" by dividing the "comfort overall" scores by specific indoor environmental quality variables, factoring temperature in summer and winter, air in summer and winter, noise, and lighting.

green tariff: can vary depending on supplier, green tariffs either provide up to 100% of energy from renewable sources, such as PV, wind, or marine power, or contribute to schemes that deliver environmental benefits.

heat flux sensor: a transducer that can be used to measure thermal resistance of elements in the building envelope.

Heat Interface Units (HIUs): also known as Hydraulic Interface Units or Consumer Interface Units (CIUs), they are heat exchangers found in dwellings which are connected to communal heating networks, and typically used for both space heating and domestic hot water production.

heat loss coefficient: see **whole house heat loss**

Heat Loss Parameter (HLP): the whole house heat loss divided by the total dwelling floor area, it is a parameter often used to compare the relative heat loss in dwellings of different sizes .

Indoor Air Quality (IAQ): the state of air within a building related to the health and comfort of occupants. Pollutants and contaminants such as VOCs, particulates and moulds can negatively affect occupant health. Proxy measures for IAQ in this study include RH and CO_2.

Low and Zero Carbon (LZC) technologies: either emit directly, or the use of which results in low or zero CO_2 emissions. Technologies which qualify as LZC have changed with new regulations, but generally these are biomass, solar, wind, and ground source heat pump systems.

Mechanical Extract Ventilation (MEV): as defined by Building Regulations Part F 2010, System 3, MEV continuously extracts air from wet rooms at a low rate. Fresh, supply air is provided naturally, typically in habitable rooms through trickle vents. MEV can be centralised, with one fan connected to multiple extract points, or decentralised, utilising multiple fans, typically one in each wet room.

Mechanical Ventilation with Heat Recovery (MVHR): as defined by Building Regulations Part F 2010, System 4, MVHR mechanically delivers fresh air to habitable rooms, while mechanically extracting air from wet rooms, thus housing two separate fans in its casing. Fresh air is pre-conditioned by capturing heat as the supply and extract streams pass through a heat exchanger, saving energy that would otherwise be required for heating cold supply air up to room temperature. However during warm conditions, it can be advantageous for the supply stream to bypass the heat exchanger so that cooler supply air can be delivered to habitable rooms. This is sometimes called summer bypass.

mono-pitched roof: buildings that have a single roof plane that covers most of the building are referred to as mono-pitched. They are sometimes used to maximise south facing roof space for the incorporation of solar panel technologies.

occupant handover: not to be confused with the handover of a building or development that occurs between the main contractor and developer, in this document the occupant handover refers to the process (and accompanying documentation) that occurs when the building occupant first moves into a newly constructed dwelling.

overheating: as defined by the **NHBC Foundation**, overheating is the accumulation of warmth within a building to an extent where it causes discomfort to the occupants. Health impacts of overheating include increased risk of illness from respiratory and cardiovascular disease. However there is no clear definition of overheating or the specific conditions under which this occurs. Nor is there any statutory maximum internal temperature in UK Building Regulations or current Health and Safety guidance. In this study, **indoor temperature thresholds** used to define instances of overheating were adapted from **CIBSE** Guide A and CIBSE TM36 2005.

parging: a construction technique in which a mixture, often a blend of lime, Portland and masonry cements, is applied to the interior surface of an external wall. Parging is often done to help seal small holes or voids in the wall to improve air tightness.

performance gap: existing in every industry, it is the gap between as-built or in-use performance and the performance intended in design. In building construction, it is often expressed as energy-related.

Post-Construction: the period just after construction, typically after Practical Completion, but prior to occupation.

Post-Occupation: the period after the occupants first move into a building.

Standard Assessment Procedure (SAP): the methodology used to assess the energy and environmental performance of dwellings. SAP is used for **Part L** as a means of assessing compliance. For this SAP calculates a Target Emission Rate (TER) for each dwelling, which is based on its actual size, shape and built form but also standard assumptions about the design, such as the type and efficiency of the heating system, and the level of insulation. The Dwelling Emission Rate (DER) is also calculated, based on all the actual design specifics. To comply with Part L, the DER must be no greater than the TER. Additionally SAP checks for other Part L requirements such as minimum U-values. SAP is also used for the production of Energy Performance Certificates and for the delivery of part of the **Code for Sustainable Homes**.

shoulder seasons: in space heating terms, the autumn and spring, when there is usually less requirement than peak season.

solar insolation: the measure of solar radiation energy

stack effect: in buildings, the movement of air driven by buoyancy. The stack effect is used as means of ventilation and to promote passive cooling through the purge of heat up and out of a building.

Structural Insulated Panel (SIPs): used for different building elements such as roofs, exterior walls and floors, they are prefabricated and modular and consist of an insulating layer sandwiched between two layers of structural board, often OSB. They combine several building components into each panel, such as air and vapour barriers, insulation, as well as structural elements.

thermal bridge: also called a cold bridge, it is a heat transfer pathway through a conductive or non-insulating material passing through an insulative building fabric layer. Thermal bridges can be repeating, such as cavity wall ties and timber studs, or non-repeating, such as lintels. Thermal bridges can cause localised condensation and mould growth.

thermal mass: the ability of a material to store heat and provide indoor temperature stability against external temperature fluctuations, or internal or solar gains. During the summer thermal mass will absorb heat and store it until it is exposed to cooler air, typically in the evening. It is used to reduce the risk of overheating and the need for mechanical cooling.

Thermoplan blocks: thin bed, interlocking breathable clay blocks which provide good U-values compared to other masonry blocks due to the air cavities in their honeycombed sections.

thin joint masonry construction: uses autoclaved, aerated concrete blocks applied with thin 2mm-3mm mortar joints. The reduced amount of mortar, when compared to traditional masonry construction, can improve the thermal properties of a building element.

U-value: measure how effective a building element is at insulating against heat transfer. The lower the U-value, the better the element is as a heat insulator.

urban density: the number of people living in an urbanised area

Volatile Organic Compounds (VOCs): certain organic chemical compounds that can be dangerous to health or cause environmental damage. VOCs have a high vapour pressure at room temperature which causes large numbers of molecules to evaporate. For example, formaldehyde is a VOC that evaporates from some paints.

whole house heat loss: also known as the heat loss coefficient, it is the sum of the fabric and ventilation heat losses, expressed in heat loss [W] per indoor and outdoor temperature differential [K].