Tackling the performance gap between design intent and actual outcomes of new low/zero carbon housing

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Abstract

The UK Government has set ambitious targets for incremental changes to building regulatory standards, which are intended to achieve 'zero' carbon new housing from 2016 onwards. Despite this driver, many low carbon solutions are untested, creating a performance gap between 'as-built' performance and 'design intent' with the potential to undermine the zero carbon housing policy.

This paper explores the available evidence on the existence and underlying nature of the performance gap and proposes solutions for addressing the problem. The paper diagnostically investigates the discrepancy between 'as designed' and 'as built' performance of a range of new exemplar low carbon housing representing a range of built forms and modern construction systems procured by a range of private developers and public housing providers in UK.

The performance is evaluated through a detailed review of design and construction specifications and processes, thermography, co-heating tests to determine actual fabric heat loss, observation of handover and mapping of occupant satisfaction. This reveals unintended fabric losses, system installation and commissioning issues, lack of proper sequencing of building works, and ambiguity of control interfaces. To ensure that the desired performance is achieved, feedback loops need to be established using a soft landings based approach for better briefing, design, graduated handover and performance in-use.

Introduction

In 2008 the UK government passed a legally binding framework to reduce the country's emissions 80 % below 1990 levels by 2050 (The Climate Change Act); since buildings account for over 45 % of overall UK carbon emissions (UKGBC, 2008), this target places considerable pressure and confidence in the UK's ability to decarbonise the building stock. The UK housing stock is the oldest in the developed world (DCLG, 2010) and a combination of incentive, regulation, voluntary and information based policies and schemes have been created to improve the efficiency of new-build and existing housing. 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 (UKGBC, 2008) by the implementation of sustainable design principles and microgeneration technologies.

A low energy or zero carbon home is a complex combination of components and systems which must perform according to expectations. With the application of improved fabric measures (such as better insulation), improved efficiencies in building services (including more efficient heating and hot water systems, lights and appliances and better controls) and the addition of low and zero carbon renewable energy generation, it is theoretically possible to meet this ambitious target. However, many of these solutions are at present untested in-use, and there is growing concern within the housing industry that, in practice, even current energy efficiency and carbon emission standards are not being achieved (Gupta and Gregg, 2012a).

There is also a lack of measured data on post construction performance in low carbon housing, but emerging studies like 'Low Carbon Housing: Lessons from Elmtree Mews' indicate a considerable performance gap between as-built performance and design intent in both building fabric and services (Bell *et al*, 2010). There is concern that this performance gap has the potential to undermine zero carbon housing policy and carry considerable commercial risk for the wider industrial sector (Zero Carbon Hub, 2010).

The government is aware of the strong evidence behind the performance gap and its potential impact on the viability of finance driven energy policies like the Green Deal[1]. In response to this, 'in-use' factors were introduced by DECC (Department of Energy and Climate Change) to make allowances for the performance gap and 'correct' expectations by applying an overall percentage reduction to calculated energy savings (DECC, 2012a). However, this can only be an interim fix while our understanding of the causes and cure for the performance gap is further investigated and improved.

This paper investigates the performance gap across four discrete low carbon housing projects procured by a small private developer (case study A), volume house builders (case study B, C) and a local authority (case study D). A building performance evaluation based investigative approach is adopted to evaluate the location and extents of the performance gap for these projects, followed by an in-depth analysis of the empirical findings to reveal the causes of the discrepancies. The root causes behind the measured performance failures were found to occur in almost every stage of the building design and construction process and involved a range of stakeholders (not restricted to the builder or the architect). In conclusion the paper recommends continuous whole systems based feedback approach (which covers all stages of the design and construction process, identifies roles and assigns responsibilities to all stakeholders) in reducing the performance gap.

BPE as a tool to reveal (and tackle) the performance gap

Building Performance Evaluation (BPE) is the process of identifying and locating the gap between 'as designed' and 'in use' performance through a systematic collection and analysis of qualitative and quantitative information related to energy performance, environmental conditions and fabric performance. Evolving from Post Occupancy Evaluation, a diagnostic evaluation of actual building performance typically taking place after construction and occupation, the term BPE was first used by Preiser and Schramm (1997) to recognize the importance of feedback at every lifecycle stage of the building. BPE involves feedback and evaluation reviews at every phase of the building delivery from strategic planning to occupancy, adaptive reuse and recycling (Preiser and Visher, 2005).

The Technology Strategy Board (TSB), UK Government's funded innovation agency, has committed up to £8 m towards a National Building Performance Evaluation programme for both domestic and non-domestic buildings, to help the construction industry deliver more efficient, better performing buildings (TSB, 2012). The programme mandates a prescribed protocol for evaluation and reporting to maintain consistency and comparability in benchmarking and analysis. TSB protocols for domestic buildings focus on the 'as-built' performance of building fabric, key energy using/generating equipment and systems, and the feedback from occupants; they are categorised based on their period of investigation (TSB, 2011) as:

1. 'Post construction and Early occupation' – 'as built' performance of the building envelope and installed equipment, effectiveness of the handover process and the occupants' initial reactions.
2. 'In-use and post occupancy' – performance of the building over an extended period of time, after fabric and systems have stabilised and the occupant are more familiar with the dwelling.

The research group, within which the authors are based, was involved in the TSB sponsored 'post construction and early occupation' stage BPE of four low carbon housing developments, each within a different procurement scenario. This paper investigates the nature and location of the performance gap in these exemplar developments and relates the findings to procurement route, construction type, ownership, and sustainability targets.

The major sources for the performance gap in the post construction and early occupation stage BPE studies tend to be discrepancies between 'as designed' and 'as built' specifications and detailing, air permeability issues, poor construction quality, lack of control over heating systems and gaps in the handover process (TSB, 2011). As a result, the investigation of these issues is mandatory within the evaluation protocol while other specific inquiries are left to the discretion of the BPE project team.

BPE studies of low carbon housing developments located in England

The four case studies from the TSB–BPE programme were chosen to represent different construction types, built forms and procurement protocols (Table 1[2]).

Understanding the extent and location of the performance gap in these studies helps gather insights into the reasons behind the deficiency and how to address it. Over six months in duration, the BPE studies focus on the following aspects of as-built housing performance, shown in Figure 1.

DESIGN AND CONSTRUCTION AUDIT

The design and construction audit is the comparison of the initial design intentions against the constructed reality to discover the rationale behind any changes made during the development and construction process and to evaluate its impact. This is carried out by analysing drawings across various stages, reviewing briefing documents and modelling inputs (including SAP calculation review), site visits, walkthroughs and interviews with developers and designers. Table 2 indicates some findings and subsequent effect on performance across the case studies.

1. The Green Deal is a UK Government initiated scheme for private investment in the carbon reduction of existing building stock. Energy efficiency improvements will be offered by the private sector to homeowners and businesses at little or no upfront cost with payment recouped through customers' energy bills (DECC, 2012b).

2. Target design rating. CSH: Code for Sustainable Homes is a holistic standard for sustainable domestic design and construction in the UK (Gaze et al., 2009).

Table 1. Overview of case study characteristics and specifications.

	Case study A	Case study B	Case study C	Case study D
Developer	*Small private developer*	*Volume House builder*	*Volume House builder*	*Social housing / Local authority*
Tenure	Freehold	Private homes ownership and Social rented	Mixed -private ownership, affordable housing rented, shared ownership	Mixed -private ownership, affordable housing rented, shared ownership
Process	Joint venture between landowners and sustainable developer -Sold to occupants	Collaboration between volume house builder UK Government funded Carbon Challenge Programme	Design for Manufacture competition aimed at sustainable, efficient and cost effective developments	Low energy, social housing development funded by local authority
No. of bedrooms, house type	three bed, mid-terrace	two bed, semi-detached	three bed, end-terrace	three bed, end / mid-terrace
Construction type	timber frame construction	Structural Insulated Panels (SIP)	Structural Insulated Panels (SIP)	a timber frame and cast hempcrete
No. of case study houses studied	1	1	1	2
Target design rating	CSH Level 5	CSH Level 6	EcoHomes Excellent	CSH Level 6
Main construction elements (as designed) U-values W/m^{2}K	-*Walls:* Rendered / wood clad timber frame, U-value: 0.16 -*Roof:* Pantile on timber, U-value: 0.14 -*Ground floor:* Sealed timber floor, U-value: 0.15 -*Windows:* Wood frame, triple glazing, U-value: 0.9	-*Walls:* Rendered SIPs, U-value: 0.12 -*Roof:* SIPS, U-value: 0.12 -*Ground floor:* Screed over insulation on beam and block, U-value: 0.19 -*Windows:* Wood frame, triple / double glazing mix, U-value: 0.9/ 1.4	-*Walls:* Brick, rendered block, cedar cladding on SIPs, U-value: 0.21 -*Roof:* Concrete/clay tiles on SIPs panels, U-value: 0.23 -*Ground floor:* Screed over insulation on beam and block, U-value: 0.2 -*Windows:* Wood frame, double glazing, U-value: 1.4	-*Walls:* Rendered hempcrete cast into timber frame, U-value: 0.18 -*Roof:* Tile on timber, U-value: 0.15 -*Ground floor:* Screed over insulation on beam and block, U-value: 0.12 -*Windows:* PVC, double glazing, U-value: 1.3/1.8
Space heating and hot water system	Wood pellet burner with radiators and solar collectors and 300 litre thermal store	Communal gas CHP (hot water distributed through underground district heating network)	Gas boiler with conventional radiators	Exhaust Air Heat Pump (EAHP); under floor heating coils and 4m^2 vacuum tube heat pipe solar collectors
Target Air tightness (m^3/h/m^2 @50Pa)	5	1	5	2
Ventilation strategy	Mechanical ventilation (MEV)	Mechanical ventilation with heat recovery (MVHR)	MVHR	MEV through EAHP
Renewables	2 kW$_p$k Photovoltaic	-	-	4 kWpk Photovoltaics
Rainwater harvesting	2500 litre store/house	Common collector	-	-

The discrepancies and major design revisions listed above can have serious knock-on effects, resulting in poor integration of services, sub-optimal detailing, inefficient installation of systems, improper commissioning and occupant dissatisfaction. A key reason for discrepancy between design and construction was found to be the progression of innovative design without a full understanding and integration of services at the early stages of the design and detailing. Some developments also experienced reluctance to proceed with particular design concepts due to the relative unfamiliarity, of all parties involved in the development, with technologies or design concepts. The common leading causes for the differences between the designed and built result across the four developments, as revealed by the design and construction audit are summarised in Table 3.

Although design preparation should ideally eliminate on-site changes, some unavoidable changes are often required; site level training is essential to establish the importance of design intentions and increase awareness about the consequences of

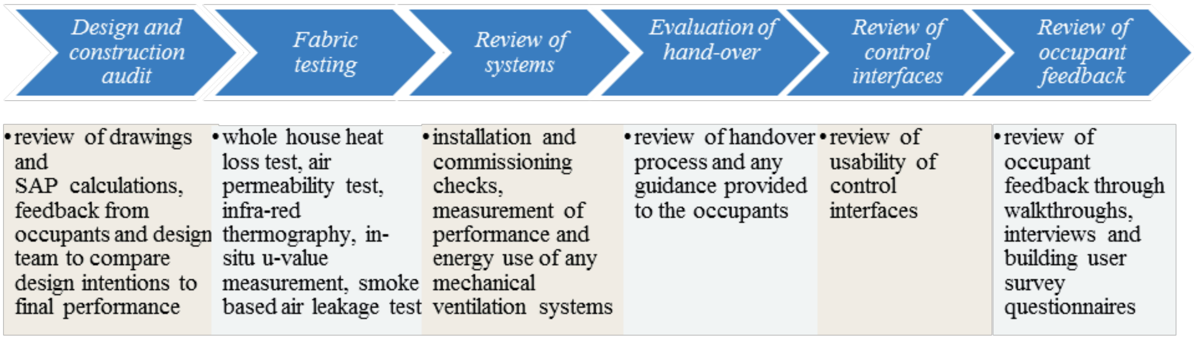

Figure 1. The mandatory study elements at the post construction and early occupation stage BPE.

Table 2. Overview of Design and construction audit.

	Design and construction audit findings	Effect on actual performance
Case A	-Original passivent system was replaced by Mechanical Extract Ventilation (MEV) unit in the roof space due to regulatory incompatibility with the design of roof framing and passivent system duct runs. -Sub-optimal location of the MEV unit led to inaccessibility for servicing, adjustment (e.g. ventilation rate cannot be adjusted for cooking) and no ventilation for ground floor bathroom	-Incomplete home ventilation – greater heat loss or uncontrolled humidity and CO_2 in unventilated bathroom – reduced indoor air quality (IAQ) -Change in base load energy use
	-Mechanical engineer not involved with integration of the space heating and ventilation strategy -Layout plans are crucial for communication between the developer, design and building teams and would help avoid conflict – The designed service zoning strategy was not communicated to the installers -Radiators added last minute due to uncertainties about the original plan for passive only heating	-Resulting in services conflicts / position of stud work in the vicinity of MEV duct runs has impacted the ducting layout and efficiency of the system -Change in base load energy use
Case B	-Originally designed to not require a heating system (through advanced levels of insulation and air tightness with heat boost built into MVHR); however, due to concerns over purchaser acceptability a full radiator heating system was installed	-This afterthought resulted in radiators in a every room that are too large, too low for ergonomic operation and located in inappropriate places with regard to efficiency or safety -Change in designed heating predictions
	-During the initial design stage the external envelope was simplified to ensure minimal thermal bridging and good airtightness	-Simple standardized detailing can help improve build-ability and ease of use. House achieved superior airtightness and low heat loss
Case C	-Concerns about durability and guarantee periods for sustainable materials (e.g. recycled wood) led to the change in specification of roofing, cladding materials. Further changes from original design in detailing and alteration to doors and windows. Change in thermal bridging airtightness assumption.	-Greater heat loss than predicted
	-changes on site have been made without full awareness of consequences (e.g. TRVs next to room thermostat, omission of radiators, omission of insulation to pipe work, etc.	-Change in designed heating prediction
Case D	-Accessibility – the EAHP was not provided in the space suggested by the manufacturer, the temperature adjustment valve for the hot water was installed out of reach	-Potentially greater hot water energy use than predicted
	-Lack of consistent communication and coordination between contractors, specialists and design team leading to Improper sealing around service outlets in the external fabric	-Impact on overall airtightness, heat loss and energy use

Table 3. Common emerging issues revealed through the design and construction audit.

	Case A	Case B	Case C	Case D
Construction changes as a result of inappropriate planning or incomplete design	✓	✓	✓	
Construction changes as a result of developer decision resulting in sub-optimal conditions	✓	✓	✓	
Mechanical, electrical and plumbing integration conflicts due to insufficient planning / no MEP guidance	✓		✓	✓
Communication and/or support failure between design team, engineers, suppliers and construction team (lack of quality control)	✓		✓	✓
Lack of on-site knowledge and training (lead to changes, insufficient work, detailing and commissioning)	✓	✓	✓	✓

change. Most onsite changes result in deviation from original SAP (UK Government approved energy rating method) calculations thereby affecting the actual energy performance.

To address this issue, building physical mock-ups of crucial design elements and design charettes at early stages can assist co-ordination between clients, design team and builders, as well as, avoid detailing problems at later stages. Service systems and renewable energy strategies must be planned at the inception stages; calculations, modelling and design should be completed before work starts on site. This will minimise on-site changes and avoid difficult and expensive abortive work or compromises. Since a lack of formalised and complete accounts of specification and drawing changes, across all the case studies, make it difficult for the developer and designers to gain and transfer learning to future projects, the contractual relationship between the design team, developer and site team needs to ensure a greater degree of communication through formalised records, the responsibility for which needs to be clearly agreed beforehand.

FABRIC PERFORMANCE

The fabric performance for each housing development was evaluated using a range of diagnostic field tests which include: a whole house heat loss test (co-heating test[3]), air permeability test[4] and infrared thermography[5].

The findings from the BPE projects showed that overall there is a gap between SAP calculated and predicted Heat Loss Coefficients (HLC) and actual measured HLC. For Cases A, B and C this gap is relatively small compared to the homes in Case D. Case D had serious issues with detailing and higher U-values than designed. Figure 2 shows the predicted and measured Heat Loss Parameter (HLP) for each case study home and compared them to UK regulatory standards. The HLP is the HLC normalised against the area of the home so that the values can be comparable. All homes but Case C would have a HLC compliant with 2010 Building Regulations and only Case B would achieve CSH Level 6.

Among the BPE studies a significant difference is found between SAP predicted thermal bridge HLC and the measured thermal bridge HLC. Notably, in two projects the SAP calculation defaults were used; a y-value (linear thermal transmittance or thermal bridging factor) of 0.08 W/m.K. Table 4 lists the y-values and the thermal bridge HLC used in the SAP calculations compared to detailed thermal simulation calculations.

In the instance where Case B used the SIPs manufacturer's specification for y-value, the thermal bridge values revealed less discrepancy. Though Case D used the SAP default y-value, which could theoretically cause the projected HLP to be above the actual, the measured HLP is above the projected and is showing the greatest difference among the cases. Most notably a cause for this may be as derived from the co-heating test; the heat flux measurements, on a single external wall in Case D.1, resulted in a mean external wall U-value of 0.47 W/m^2K. This measurement is significantly higher than the designed U-value of 0.18 W/m^2K and furthermore unacceptable even under 1985 Building Regulations for England and Wales (Killip, 2005).

To further contribute to discrepancies between calculated and measured, all homes showed significant levels of heat loss through party walls following heat flux tests. Cases A and B showed similar results with around 2.8 % of total building heat loss being lost through the party wall. In Case A, the clear weak point was heat loss through the floor (Figure 3, left). Case C exhibited the greatest percentage of total heat loss through the party wall at 7.9 % of total house heat loss. The measured heat loss was found to be 67 times greater than theoretically expected based on the SAP party wall U-value of 0.2 W/m^2K. Based on thermographic analysis (Figure 3, right), the wall appeared to be poorly insulated allowing heat loss to escape through the parapet. Both design and construction requires greater understanding and attention to detail with regard to thermal bridges and party walls.

Air permeability tests revealed a noteworthy gap between designed and actual air tightness in the homes. The greatest

3. Co-heating testing is a post-completion test that is designed to quantify as-built whole building heat loss in a completed unoccupied house over a period of at least three weeks when a temperature differential of at least 15 °C can be achieved. The heat loss is sub-categorised by fabric (including thermal bridging) and ventilation heat loss measured as the Heat Loss Coefficient (HLC) (W/K).

4. Air permeability tests or blower door tests are performed before and after the co-heating test to help establish the air permeability and the heat loss due to air infiltration and exfiltration through the building fabric alone. Ventilation routes such as mechanical ventilation heat recovery (MVHR) units are sealed during the tests.

5. Infrared thermography visually renders thermal radiation from building elements helping locate heat related construction faults and leakage.

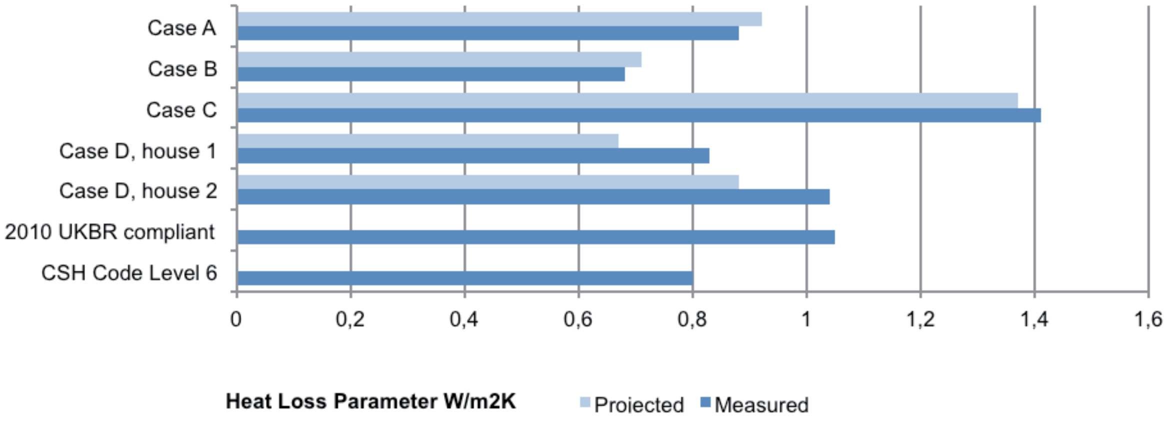

Figure 2. Heat loss parameter for tested case study homes compared to UK regulatory standards. The 2010 UK Building Regulations (UKBR) compliance figure is based on SAP calculations using a two-storey detached house with an area of 105 m² (GHA, 2011). CSH requires a minimum HLP of 0.8 W/m²K to achieve a Level 6 designation (Gaze et al., 2009). The SAP projected HLC values do not include mechanical ventilation so that they may be comparable to the co-heating methodology which requires that all ventilation is sealed.

Table 4. Thermal bridge calculated projections versus simulated measurements.

	Thermal Bridge W/K (SAP)	Thermal Bridge W/K (measured)	Y-value (SAP)	Y-value (simulation)	SAP Thermal bridge overestimation
Case A	20.36	6.65	0.080 (SAP default)	0.026	206%
Case B	5.65	6.22	0.030 (from SIPS manufacturer)	0.033	-9%
Case C	17.84	10.11	0.080 (SAP default)	0.048	76%
Case D.1	16.86	Not calculated (N/C)	0.080 (SAP default)	N/C	N/C
Case D.2	21.45	Not calculated (N/C)	0.080 (SAP default)	N/C	N/C

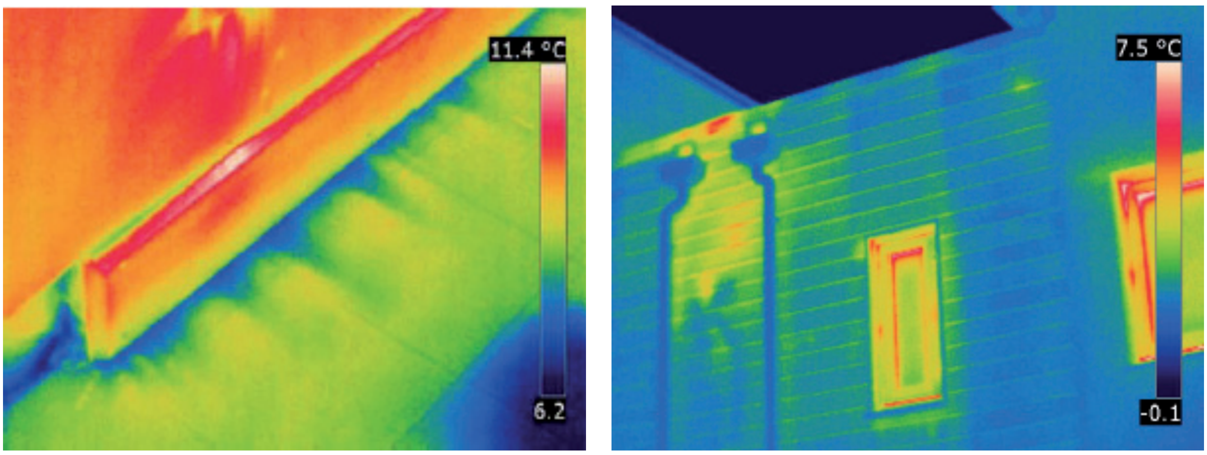

Figure 3. Thermographic images of heat loss through the floor / wall junction of the party wall in Case A (left) and heat loss through the parapet junction of the party wall in Case C (right). Note: the left image shows unfinished skirting board along the floor.

concern is in Case D, where both homes missed the target by a large amount, especially Case D.2 with air permeability over twice as high as expected (Figure 4). Apart from the construction quality, most likely the built-form, i.e. end-terrace, of Case D.2 contributes to the discrepancy between the measured and designed air pressure values. Case B performed exceptionally and based on observation, even still could have improved further with more care taken around windows and door threshold seals. The results achieved by Case B undoubtedly benefited from the modifications to the original design in response to concern for thermal bridges and air tightness. In Cases A, C and D, better air tightness would have resulted from a higher quality of detailing at key junctions, skirtings and service penetrations. Specifically, for Case D, air leakage was found in a number of places: through penetrations in ground floor bathrooms, electrical cupboard, solar and MVHR cupboards, below skirting boards and around external doors on the ground floor. All cases would have benefited from more detailed care around door and window thresholds and seals and service penetrations. The roof gables were also weak points for some homes. Air permeability test failures can result in delayed handover, time and payment disputes and costly remedial works. Some air leakage pathways are extremely difficult and expensive to fix.

REVIEW OF SYSTEMS INSTALLATION AND COMMISSIONING

A commissioning review is undertaken to ensure that the commissioning of equipment and services is complete and the design and operational strategy was capable of creating the desired conditions. The review includes interviews and walk-throughs with the installation engineers, inspections of the installed systems (including measurement of the ventilation system flow rates). Table 5 presents the findings and effect on performance from the systems installation and commissioning review.

Reflecting on the performance gap created by insufficient communication and on-site knowledge, inadequately planned ductwork with scarce insulation was observed in all cases. Additional offsets and bends in the ductwork potentially results in increased system resistance and noise. Inefficient ductwork in some cases resulted in MVHR efficiency reductions. With regard to the imbalances found, according to the Passivhaus Institute, imbalances of 10 % can contribute to efficiency loss of up to 6 %. Primary pipework was found lacking insulation in all cases. This misstep is surprising and unsettling given the original design intent for the homes and standard regulatory coverage of this issue. This is clearly an area where increased training and awareness will have a large impact on closing the gap. As a lesson learned, installation and commissioning procedures need to be more robust, including appropriate certification ensuring knowledgeable engineers. Furthermore, before specifying suppliers, the design and construction teams should ensure that there is a sufficient post-installation support and maintenance guarantee.

REVIEW OF CONTROL INTERFACES

Control interfaces are the meeting point between the users and the building technology. A review of the control interfaces normally takes place before the official handover to investigate the relationship between the design and usability of controls and the potential effect that they could have during the dwelling's occupancy. Table 6 lists an overview of the findings and effect on performance of the control interfaces in the case studies.

Lack of provision of clearly labelled, decipherable and accessible controls was the common leading issue in all four case studies. Specifically, provision of usable controls (including boost function) for the mechanical ventilation system was an issue for all cases. In Case A the boost controls were located out of reach in a storage cupboard, while the ideal location would have been in one of the kitchen cupboards, easily accessible during cooking. In case study C the MVHR unit is not located for easy access for filter maintenance. In contrast, in case study B the MVHR unit was relocated for ease of access during construction. Unfortunately this has had a negative impact on the efficiency of the system. This case highlights the need for integrating a design strategy and servicing design for heating and ventilation systems. A detailed and coordinated services layout plan showing location of controls will help to solve issues of accessibility and efficiency loss.

REVIEW OF HANDOVER PROCESS AND USER GUIDANCE

The handover review is an evaluation of the handover process and documentation homeowners receive before and after moving into their new home. This is especially important for low carbon buildings with innovative design strategies and complex new technologies. The purpose of the review is to establish whether the information that the home owners receive is sufficient in communicating the intent and operation of the new home without being overly technical or confusing. The review aims to provide guidance on how this communication process can be improved. Table 7 lists the findings and from the handover review for all cases.

The review of the handover process and its impact on overall performance reveals some common trends as shown in Table 8.

With regard to developer type, it appears that from the small sample, larger developers, particularly the Local Authority (Case D) already having experience with a large stock of homes and tenants, are more successful in organising and delivering comprehensive and helpful guidance and handover sessions. The larger organisations tend to have the financial resources and manpower to dedicate to successful handovers and continued assistance, hopefully ensuring awareness of appropriate operations of the home. Successful handovers are conducted by one responsible party, trained on all systems prior to handover, providing a single point of contact for the occupants.

The findings reveal that a phased approach is most successful for the handover. Initial group training sessions may be conducted before the move in, when installation and commissioning is complete for all systems. This provides an overview of household and common development features and an opportunity for occupants to be further informed by listening to their neighbours' questions and concerns. Home user guides with simple, comprehensive and visual diagrammatic guidance for users is ideally provided at this stage. The guide should diagrammatically depict locations of sustainable features, emergency controls, maintenance procedures and a 'do's and don'ts' section for quick reference in a durable long lasting document. Technical details and manuals must only be included in appendices, as they often confuse and overload the occupants.

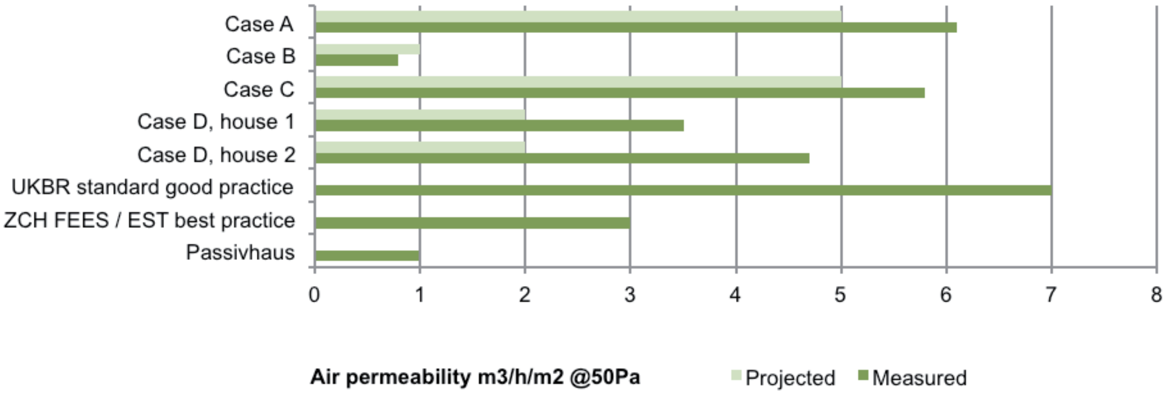

Figure 4. Air permeability for tested case study homes compared to practice standards.

Table 5. Overview of review of systems installation and commissioning.

	Findings from review of commissioning	Effect on actual performance
Case A	-Lack of training, coordination and communication regarding installation and commissioning of heating and ventilation systems -Commissioning failure: MEV was found to be delivering inadequate air flow rates (below regulations)	-Greater heating energy use than predicted -Negative impact on IAQ
Case B	-External connection ducts long and poorly insulated -MVHR found to have an imbalance between supply and extract of up to 30%	-System inefficiency -Greater than predicted energy use
Case C	-Ventilation flow rates are lower than recommended due to flexible ductwork and incorrect commissioning	-Negative impact on IAQ
	-Limited knowledge of systems and materials lead to installation of both thermostatic radiator valves and room thermostats in the same room (conflicting controls)	-Change in designed heating prediction
Case D	-MVHR kitchen extract boost too low -Insufficiently planed ductwork: added offsets and bends -Heating controls and zone thermostats not connected, incorrectly installed (first floor heating inoperable)	-Negative impact on IAQ -Increased system resistance and noise -Greater heating energy use than predicted due to attempt to compensate for unheated spaces and unconnected thermostats

Table 6. Overview of review of control interfaces.

	Findings from review of control interfaces	Effect on actual performance
Case A	-No control for changing ventilation rates. -Electrical controls poorly labelled	-Increased heat loss and energy consumption, possible impact on IAQ -User discomfort, increased humidity
Case B	-Unclear heating controls (boiler programmer, room thermostats) -MVHR controls unclear and difficult to operate; little indication of system response	-Compromises on the user's ability to control the systems for optimal comfort and energy consumption
Case C	-Heating and ventilation equipment is inaccessible -Location of MVHR boost switch inaccessible and non-compliant with Building Regulations -MVHR, heating and hot water controls not intuitive -Little indication of MVHR responsiveness or faults	-Negative impact on indoor air quality and user satisfaction -Potential negative impact on energy use
Case D	-Two conflicting control approaches for the house: masterstat and room thermostat -Oversimplified interface lacking clear labelling and indication of system's response	-Impacts user's ability to understand and control the systems for optimal comfort and energy consumption -Potential negative impact on energy use

Table 7. Overview of review of handover process and user guidance.

	Findings from review of handover process	Effect on actual performance
Case A	-Lack of feedback in all stages; one sided handover (no interaction with occupants); guidance documents lacked diagrams and clear, simple explanations of the heating and ventilation systems, emergency cut off points, etc.	-Occupants unable to access and use the environmental controls properly – impact on comfort and energy consumption
	-Responsibility for the handover was not defined. The developer expected individual suppliers to carry out handovers of their systems.	-No single point of contact for future doubts/trouble shooting
Case B	-Handover review not carried out, prototype is unoccupied	Not applicable
Case C	-Well-presented and informative master manual and home user guide; charismatic demonstrators	-Positive impact on confidence of buyers and trust between developer and occupants
	-Explanations of the MVHR, ventilation and heating controls contained errors and did not demonstrate maintenance procedures like filter replacement	-Impact on user understanding of how to control, maintain and operate the systems
Case D	-Home user guide created by the council (developer) in collaboration with the architects. Guide did not have a do's & don'ts section; photos showing location, controls for various systems	-Tenants initially found the control interfaces confusing
	-Group induction tours conducted before occupation -Individual household training day was conducted after occupation	-Useful for occupants to know about their neighbours' concerns and questions. -Occupants found combination of induction tour and training day very useful. Feedback on the initial induction tour could be addressed in the training tour

Table 8. Common emerging issues highlighted by the handover review

	Case A	Case C	Case D
Guidance and handover needed to be more comprehensive	✓		
Home user guide would have benefited from more clarity simplicity and diagrams	✓	✓	✓
Handover lacked demonstrational and operational hands-on experience	✓	✓	
Handover held at inappropriate time for occupant thereby sacrificing full comprehension	✓		

The handover/training tour is typically conducted for each house a few weeks after move in, when the occupants have had time to familiarise themselves with the new home and to develop their own questions. This final tour should involve occupant hands-on experience in controlling the MVHR, heating system and electricity panel. This tests the effectiveness of the induction, encourages feedback and helps actively involve the occupant.

OCCUPANT SURVEY, INTERVIEWS AND WALKTHROUGHS

Occupant opinion, satisfaction and concerns were gathered for case study A, C and D from building user survey questionnaires, semi-structured interviews and walk-throughs with the occupants in the first three months after occupation. Case study B was designed as an unoccupied prototype for future development. Table 9 lists the positive and negative feedback from the occupants of the homes.

It is noteworthy that although all occupants perceived the handover process as useful, the effectiveness and impact of the handover varies considerably. Table 10 summarises the key issues in common for all cases.

Despite the rigorous modelling and innovative design, the thermal comfort levels reported in low energy, high performance houses are not always satisfactory. Thermal comfort is a significant variable in the performance gap. Energy use in the home is heavily dependent on the occupant's perception of comfort and their attempts to attain comfortable conditions. The satisfaction with thermal comfort can be closely linked with the level of understanding and control over heating and ventilation systems. Resolving the issues of comfort and control efficiently is essential for closing the performance gap. Occupants in Case D describe actively using the controls to adjust the internal environment and are generally more satisfied with the comfort levels. Alternatively, errors in commissioning for Case A (fan speed constantly on maximum, low boiler set point temperature) have had negative impacts on comfort levels. These preliminary results indicate the importance of the handover process in helping occupants understand how to control their environment, verification and accountability in the commissioning process, and the role of intuitive and responsive control mechanisms.

Table 9. Overview of feedback from Occupant survey, interviews and walkthroughs.

<table>
<tr><th></th><th>Positive feedback</th><th>Negative feedback</th></tr>
<tr><td rowspan="3">Case A</td><td rowspan="3">-Good daylight levels and pleasant views</td><td>-Induction process and handbook inadequate; induction timing not ideal; poor aftercare and trouble shooting</td></tr>
<tr><td>-Occupants feel they have little control over heating and ventilation, poor access to controls
-Poor detailing; noticeable commissioning flaws;
-Flexible ducting for MEV resulted in increased noise levels; mixed feelings about layout, appearance and location</td></tr>
<tr><td>-Lack of designed, accessible storage (especially for wood pellets for the boiler) reduces satisfaction and usability of the wood boiler system</td></tr>
<tr><td>Case C</td><td>-Satisfaction with location, contemporary look, design, open plan, daylight
-General satisfaction with comfort, temperatures, noise and lighting
-Handover process was useful</td><td>-Misconception about MVHR function and maintenance; -Poor thermal comfort: too hot in summer and cold in winter, dry in both seasons; All occupants report overheating in summer</td></tr>
<tr><td rowspan="3">Case D</td><td rowspan="3">-Satisfaction with location, contemporary look, design, open plan, daylight
-General satisfaction with comfort, temperatures, noise and lighting
-Handover process was useful
-Majority satisfied with design, liveable space, thermal comfort, air quality, daylight quality, sense of control over comfort;</td><td>-Poor acoustic performance of party walls; Privacy conflict with full height windows in bedrooms; High ceilings caused problems for cleaning and operation of roof lights.</td></tr>
<tr><td>-Lack of visitor parking, leaky doors and windows; lack of appropriately sized storage and cupboard space; lack of power supply in garage.</td></tr>
<tr><td>-Confusion about mechanical ventilation
-Unhappy with lack of storage</td></tr>
</table>

Table 10. Common emerging issues between case study developments.

	Case A	Case C	Case D
Noise problems reported	✓	✓	✓
Occupants do not have a sense of control	✓	✓	
Lack of understanding equipment / systems	✓	✓	✓
Lack of adequate storage	✓	✓	✓

Table 11. Common emerging issues between case study developments.

	Case A	Case B	Case C	Case D
Construction faults as a result of post-design changes	✓	✓	✓	
Inadequate or poorly detailed insulation and air tightness at junctions	✓		✓	✓
Greater heat loss through party walls than predicted	✓	✓	✓	N/A
Inadequate installation and commissioning of systems	✓	✓	✓	✓
Controls not accessible, non-ergonomic or difficult to understand	✓	✓	✓	✓
Occupant dissatisfaction with provision for storage	✓	N/A	✓	✓

Note: N/A indicates that the issue was not measured or data was inconclusive. Though occupant dissatisfaction with storage space is not directly linked to the overall carbon emissions of a building it is a recurring theme in developments. Indirect problems may occur as in Case C, the MVHR cupboard is doubling as storage space and being overwhelmed with occupant belongings, limiting access to the unit.

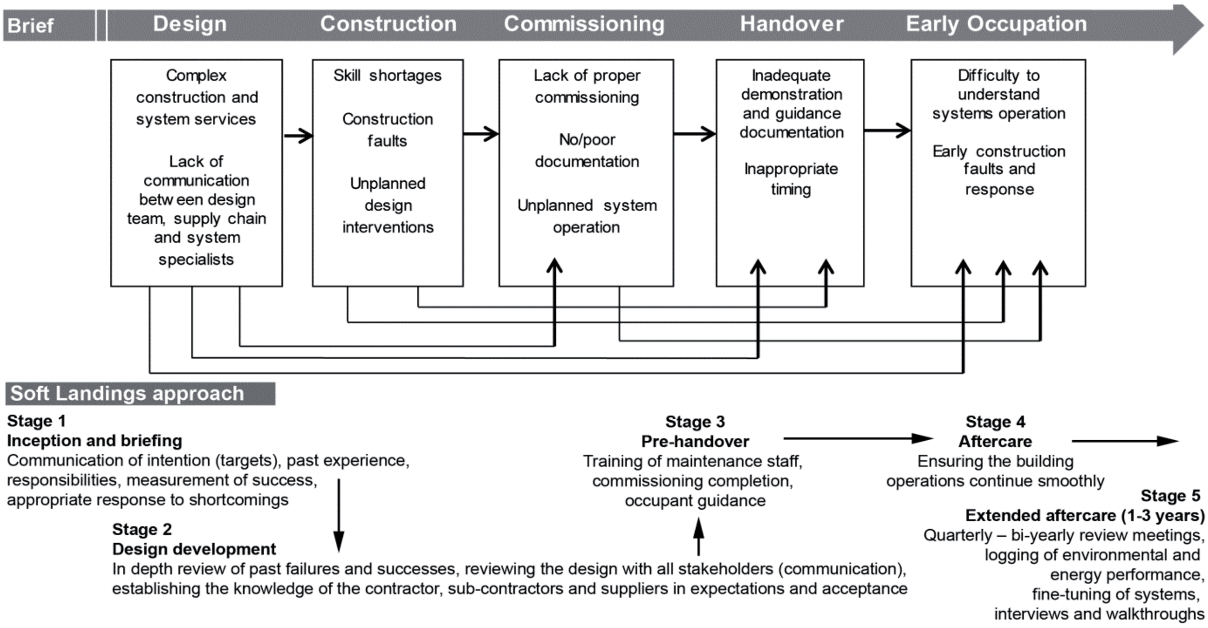

Figure 5. Diagram of the flow from design to early occupation and performance gap issues that can arise.

Discussion on tackling the performance gap

The evidence for the performance gap gathered across a variety of built forms and modern construction systems show that while certain discrepancies may have begun due to a particular briefing, construction, specification or design error, the extent of the resultant performance gap is either amplified or alleviated by the effectiveness of the troubleshooting response from the design team, construction team or developer. A common theme between all case study developments is the difficulty caused by post-design, mid-construction changes to the homes. These changes can be a result of initial miscommunication in the design and planning phase, last minute client misgivings or a design compromise in response to limited knowledge of subcontractors et al. Table 11 lists some common causes behind performance gap which were shared between most cases and are notable causes for the performance gap.

Much of the issues listed above are the result of communication drawbacks. These are a result of weaknesses in drawn communication of intention, communication of expectations (e.g. is the construction team capable of working with a specified material or installing equipment), onsite evaluation of work done and communication of expectation for improvement. To evaluate the work in progress and to ensure coordination and met expectations, it is vital that project teams stay engaged after practical completion to guide occupants during the initial period of occupation, and to stay involved for up to three years providing professional aftercare, and for documenting the lessons learned for future development. This initiative, called Soft Landings (SL) is being adopted in flagship non-domestic building projects in the UK, and it is yet to be used in a low-carbon housing project. Developed by the Usable Buildings Trust, SL approach provides a five stage alternative to the conventional brief, design, build and occupy system, which aims to close the performance gap (BSRIA, 2009). Stages 1 and 2 are designed to avoid any problems in design and construction from the outset. Communication and review during the construction process should extend between stages 2 and 3. Stage 4 is a slow gradient of a handover which includes more involvement of a resident on-site attendant for non-domestic. As the SL approach was developed for non-domestic application, stages 4 and 5 may be a little less intensive depending on the acceptability of the occupants. Figure 5 indicates where potential causes for discrepancies in the performance gap occur (from design to early occupation stage) and how a SL-based approach can reduce this gap.

Table 12 summarises leading issues for each case study, recommendations for each stage and overall emerging lessons that help reveal and tackle the performance gap. Learning from cases such as these, where issues arise in the process from design to early occupation is helpful in tackling the performance gap and achieving low/zero carbon housing in practice. There is much to learn and feed forward from these case study projects about the importance of communicating expectations, goals, capability and requirements amongst all stakeholders.

Conclusion and recommendations

As building regulations become more stringent in response to the UK Government's targets for 'zero' carbon new housing, the building industry will be required to meet higher fabric standards, home performance and furthermore provide evidence of performance compliance. To remain competitive it is recommended that the Soft Landings and BPE methods are followed to reveal and close the performance gap. It is essential that all teams document, learn from and feed-forward results for future design and construction decisions.

RECOMMENDATIONS FOR POLICY-MAKERS

The on-going support of programmes like the TSB's Building Performance Evaluation programme provides valuable lessons learned; without this programme the valuable lessons learned

Table 12. Leading issues, recommendations and emerging lessons that will help reveal and tackle the performance gap of new low and zero carbon housing.

Case study element	Main findings				Recommendations for each stage
	Case study A	Case study B	Case study C	Case study D	
Design and Construction Audit	-Sub-optimally located MEV resulted in IAQ issues and increase in base load energy use -Lack of formal drawings	-Change to conventional heating system increased consumption -Simplified envelope improved air tightness	-Changes to detailing, specification leading to increased heat loss	-Improper sealing around service outlets in the external fabric - impact on airtightness, heat loss and energy use	-Complete systems planning and integration at initial stages; improved onsite communication, training & support -Communication of expectations
Fabric Performance	-Sub-optimal party wall insulation and detailing resulting in more heat loss than designed	-Simplified envelope and thermal bridging improved air tightness and heat loss -Physical mock-ups of difficult or unusual details proved essential in superior performance	-Sub-optimal party wall insulation and detailing resulting in more heat loss than designed	-Unfamiliarity with hempcrete resulted in sub-optimal detailing and significant gap in air permeability and heat loss expectations	-Interval site work inspections of performance-dependant milestones -Party wall construction and detailing needs more focus
Review of Systems installation and commissioning	-MEV found to be delivering inadequate (below regulation) air flow rates -Primary pipework not insulated contributing to heat loss	-External connection ducts long and poorly insulated – reduction in MVHR efficiency. -MVHR imbalance up to 30% – further efficiency loss	-Ductwork and improper commissioning – low flow rates -Undersized services and appliance cupboards – maintenance and access issues and inefficient use of systems	-Insufficiently planed ductwork – leading to additional offsets and bends potentially resulting in increased system resistance and noise	-Installation and commissioning procedures need to be robust, knowledgeable engineers -Stronger coordination for services, space needs and design
Review of Control Interfaces	-Lack of trickle vents; no controls for ventilation rates; controls -poor labelling, good access	-Unclear heating controls; MVHR controls – difficult to operate, no indication of system response	-Controls – not indicative, intuitive or accessible; impact on IAQ and occupant satisfaction	-Multiple control approaches confusing; oversimplified interface compromises user's control of systems	-Design controls at initial stages to be accessible, intuitive and indicate response/faults.
Review of Handover Process and User Guidance	-Individual suppliers carried out system handovers: no single point of contact for future	-Review not carried out – prototype unoccupied	-Staff were charismatic but the handover had errors, lacked hands-on demonstration	-Phased approach to handover was effective; guide could be clearer, more visual	-Well timed, phased training; hands on demonstration; visual, simple yet comprehensive guides
Occupant Survey, Walkthroughs and Interviews	-Dissatisfaction over handover, controls, detailing, storage, aftercare and trouble shooting		-Satisfaction with design, comfort, noise and lighting; Summer overheating reports	-Satisfaction with design, thermal comfort, air quality, daylight quality, control over comfort	-Empowerment through sense of control – occupants need to fully understand how to operate building and systems
Main lessons learned from case studies	-Full understanding, decisions, specification and integration of services needed at early stage in design and detailing process -Full awareness of consequences of changes are needed by all parties	-Commendable pre-planning with regard to fabric efficiency, physical mock-ups of details and prototype exploration by developer -More careful integration of services needed	-Training is needed on site to communicate the importance of maintaining design intentions when unavoidable changes with lasting effect are required	-Proper selection, training and coordination of building contractors and careful application of innovative low-carbon building methods is essential	

from the presented case studies would not be available. The government, with the intention to improve the housing stock must work with industry to develop a national database, learning programme which would involve education and training for design and construction, continued research and further support for prototype development and testing. The performance gap in theory can be created by the tools used for design. If the regulatory tools create flawed performance expectations, the gap will be greater than that which should have realistically been predictable. It is therefore suggested that the regulatory tools continue introspection in response to the findings in case studies such as these (GHA, 2011).

- Soft landings and post-occupation evaluation and monitoring should be incentivised.
- Diagnostic testing should be made mandatory. For example, a sample of homes in all new low carbon housing developments undergoes co-heating tests while all homes have thermography documentation.
- Sustainability certification (e.g. CSH) should be limited to homes that have had BPE/diagnostics.
- Performance driven targets set in Building Regulations.

RECOMMENDATIONS FOR DEVELOPERS

As has been documented some gaps are common to all new build housing irrespective of developer size and scope. The performance gaps tend to be the result of how the briefing, design and construction processes are communicated and resolved. Most notably, it is important that in any case where a developer (e.g. Case D) is inflexible in choice of contractor and construction team, appropriate training should be sought before exploring construction with new materials or equipment. The performance gap in developments by small developers may be more difficult to resolve as opposed to those by larger developers or local authorities. Small developers may not have the necessary human and technical infrastructure or resources to resolve issues and provide well-planned handovers followed by customer service as was reflected in the lower occupant satisfaction in Case A.

- Developers need to share and seek experience. This is especially necessary for the smaller developers that may have less experience and more to lose.
- The developer should take the lead on initiating and ensuring communication between all stakeholders.
- Ensure capability and experience of all stakeholders involved.
- Coordinate training for support staff after occupation (e.g. Case D – local authority development).
- Create comprehensive and visually diagrammatic guidance for users by referencing best practice guidance and handover processes.
- Incentivise prototype testing – prototypes, as in Case B, are commendable in testing new materials and methods and in doing so tackling the performance gap before full scale development proceeds.
- Incentivise Soft Landings and post-occupation evaluation and monitoring to future occupants.

RECOMMENDATIONS FOR THE BUILDING INDUSTRY

The following recommendations are selected lessons learned from the presented case studies relevant for the building industry:

- Simplify external envelope to ensure minimal thermal bridging and optimised airtightness. Simplicity reduces errors in all phases from design to construction (design team).
- Communication and involvement of all parties involved in the design and construction process (including client and suppliers) through all stages is essential. This includes documentation and agreement for all changes to be shared for successful future development. (Issues involving the occupant such as systems control comprehension and storage dissatisfaction are lessons learned post-occupation. It is imperative that these problems are recognised, enter the feedback loop and are resolved in future development.).
- Physical mock-ups of innovative or unconventional design solutions have proven to be indispensable (building and design team).
- Consider the usability of all control interfaces; discuss the interface design with manufacturers and provide feedback on controls (industry and supply chain).
- Provide hands on training of equipment and controls for occupants and staff preferably after commissioning has been satisfactorily completed and the occupants have had time to settle in and develop personal queries around the operation of the home.
- All highly insulated and airtight houses can be at greater risk of summer overheating now and more so in the future as a result of changing climate conditions. This risk should be considered in all designs and avoided through measures such as appropriate shading techniques and reduced internal gain (Gupta and Gregg, 2012b) (design team).
- The installation and commissioning process for services (e.g. low carbon systems) is critical; ensure technicians are knowledgeable about the process and documentation is thorough. Provide on-site training at all levels to ensure appropriate fitting of materials and equipment (industry and supply chain).

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