Technology Strategy Board
Driving Innovation

Information Paper

Lessons from AIMC4 for cost-effective fabric-first low-energy housing

Part 5: As-built performance and Post Occupancy Evaluation

Christopher Gaze

Image courtesy of Crest Nicholson plc.
AIMC4 homes at Epsom

STEWART Milne GROUP

Crest NICHOLSON

BARRATT DEVELOPMENTS PLC

H+H

bre

Executive Summary

The AIMC4 homes were subject to as-built testing on completion and post occupancy evaluation, including measurement of energy performance along with other parameters during their first year of occupation.

There are challenges for measuring the performance of homes whether it be through as-built testing such as co-heating or through post occupancy monitoring. There are also difficulties around identifying the causes of difference between the performance of homes and the results from SAP[1]. This is illustrated in Figure 1.

The AIMC4 consortium experienced considerable difficulties with the co-heating test and would agree with the Zero Carbon Hub that, "Although it has merit as a tool to inform research and development, its use as a single industry wide end of line gateway is impractical."[2] The consortium would favour post occupancy monitoring as a way of measuring performance, but there is a need for cost-effective equipment which is reliable and robust, unlike the choice available at the time of the project which was both expensive and unreliable.

AIMC4 results need to be interpreted with the understanding that the sample size is small and that the reasons for performance differences in energy use are difficult to understand and assign.
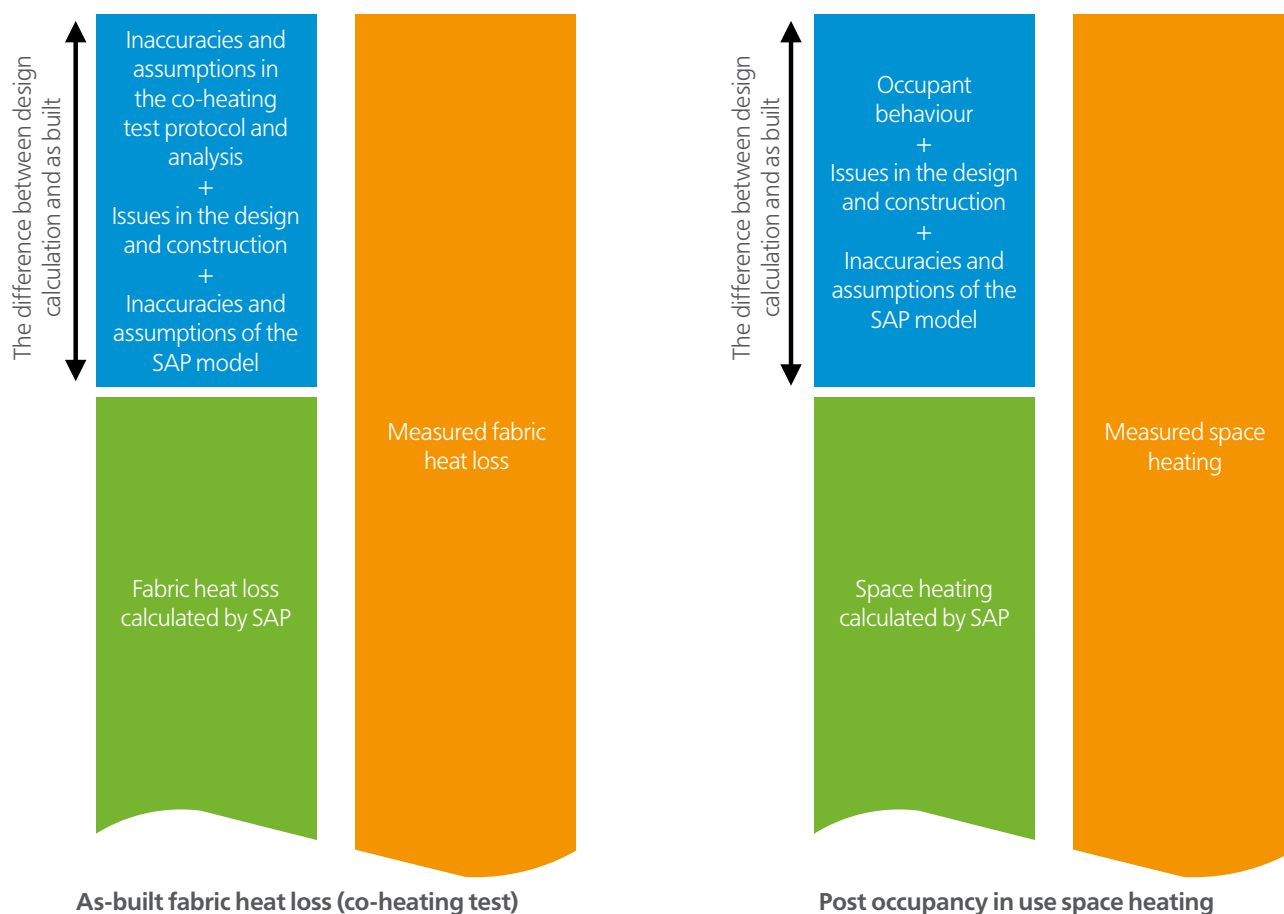
The overall results for the fourteen dwellings that were monitored were that five of the homes were within ±10% of the regulated energy usage shown in SAP. Four homes used less energy than SAP (76-86%) and five homes used more (up to 196%).

The learning from this research highlights some potential areas for improvement in SAP, in home design and in construction practice. For example, the triple glazed windows and waste water heat recovery systems have performed particularly well.

The results also highlight, the perhaps obvious point, that how the occupants use their homes is a major driver for their performance, and that this can have a larger impact on energy usage than the low energy design features of the homes. This shows the necessity for occupant centred design and effective communication with purchasers. More details can be found in the Lessons Learnt section at the end of this paper.

The occupants find that the AIMC4 homes are comfortable and pleasant to live in with no indications of any health or additional maintenance issues. They are overwhelmingly satisfied with their fuel bills.

Figure 1: Diagram illustrating the difference between predicted design and as-built energy performance as measured by the co-heating test and predicted design versus post occupancy performance.

The difference between design calculation and as built

Inaccuracies and assumptions in the co-heating test protocol and analysis
+
Issues in the design and construction
+
Inaccuracies and assumptions of the SAP model

Measured fabric heat loss

Fabric heat loss calculated by SAP

As-built fabric heat loss (co-heating test)

The difference between design calculation and as built

Occupant behaviour
+
Issues in the design and construction
+
Inaccuracies and assumptions of the SAP model

Measured space heating

Space heating calculated by SAP

Post occupancy in use space heating

[1] SAP is the Government's Standard Assessment Procedure for Energy Rating of Dwellings.
[2] Closing the gap between design and as-built performance – new homes, Interim Progress Report, July 2013

Introduction

This Information Paper is Part 5 of a series of 7 Information Papers about the AIMC4 applied research project which was created to research, develop and pioneer the volume production of low-carbon homes for the future that would achieve Level 4 (energy) of the Code for Sustainable Homes without the use of renewable energy.

This paper focuses on the as built performance and post occupancy evaluation of the homes through interviews and measurement yielding both quantitative and qualitative information.

The AIMC4 consortium has always been focused upon the actual performance of the homes and in particular the experience of occupants. During the course of the project the topic of "as-built performance" has risen up the industry agenda and the paper reflects this heightened awareness.

The original suite of four Information Papers presented an overview of the project, supply chain development, technical development and Lean techniques. This paper follows on from Part 3, which focused on the technical design step and links to Part 6 which looks specifically at Ventilation and Indoor Air Quality and Part 7 on commercial matters. The papers are available for free download at www.aimc4.com.

What is AIMC4?

AIMC4 is a unique partnership of companies, created to research, develop and pioneer the volume production of the low carbon homes for the future. It stands for the Application of Innovative Materials, Products and Processes to meet the Code for Sustainable Homes Level 4 Energy Performance.

The AIMC4 Consortium was set up in 2009 to develop and apply innovative materials, products and processes to meet the Governments Code for Sustainable Homes, Level 4 energy performance, through innovative fabric and building services solutions only, thus embedding reduced carbon emissions within the performance of the dwelling.

The Consortium members comprise developers, Stewart Milne Group, Crest Nicholson PLC and Barratt Developments PLC , who were responsible for the design and build of the energy efficient homes, the Building Research Establishment (BRE) advising on innovative solutions and evaluating the technical issues and H+H UK

Ltd a supplier of Aircrete concrete products. BRE Scotland analysed and evaluated both the performance of the homes and occupant responses and behaviours.

The ground breaking project was worth £6.4m, of which £3.2m was invested by the UK's innovation agency, the Technology Strategy Board with the other £3.2m coming from the members.

The key to the success of the project has been to engage with both known and new suppliers at all levels to develop design solutions and processes to deliver Code 4 (energy) homes through energy efficient fabric and building services solutions, without the use of renewable technologies.

Achieving this goal will not only assist in meeting the Government target of zero carbon homes by 2016, but will reduce costs, create new UK supply chains, generate new build systems and processes and ensure homes are designed that meet consumer needs without confusing or costly technologies.

What is the Code for Sustainable Homes?

The Code for Sustainable homes is part of the Government's programme to improve the sustainability of new dwellings, in particular with a view to national targets for reducing carbon dioxide emissions, but taking a more holistic approach by considering a wide range of environmental and social impacts of new homes. It is used in England, Wales and Northern Ireland.

The Code has six performance levels – Levels 1 to 6, and assesses both new dwellings and the development site against nine categories. The category of relevance to this project is the mandatory requirement for energy efficiency at Code Level 4

(see Code for Sustainable Homes, Technical Guide, November 2010, Department for Communities and Local Government), that requires an improvement in dwelling emission rates of 25% over those set out in the English Building Regulations 2010 Approved Document Part L1A (in earlier versions of the Code this used to be a 44% improvement over the 2006 Regulations – which is roughly equivalent).

At the start of the project it was anticipated that this dwelling emission rate would be incorporated into English Building Regulations in 2013.

Background

As-built testing and measurement

A series of as-built tests were carried out on the homes:

– Airtightness

The standard air door blower test was conducted on all of the AIMC4 homes by accredited practitioners. As well as the required end of the build test for regulatory compliance, air-tightness was also evaluated at several stages during construction and one year after occupation.

– Sound Performance of Party Walls

This standard test was completed on all homes with party walls.

– Heat flux – Party Wall Only

Heat flux tests use heat flux sensors to measure the energy flow through a building element. As the co-heating tests were planned for some of the homes, heat flux testing was only conducted on three party walls, as these were all going to be to the then new "zero U-value" design.

– Whole House Heat Loss (Co-heating)

This is a research tool that is designed to assess the overall "steady state heat loss co-efficient". The test involves heating the home with electrical fan heaters to a temperature warmer than the outside surroundings and then calculating the energy used to maintain this temperature. The test was carried out on eight homes.

– Thermal imaging

Thermal imaging shows radiated heat coming from a home. The homes are pre-heated and are photographed on a cold night. While the images do have a temperature scale, this cannot be used to measure heat losses and they are therefore a qualitative tool.

Post-occupancy monitoring

The post-occupancy research included both the measured as-lived in performance of the homes, plus five interviews with the occupants spread over the first year of occupation. The following were measured on all the homes with readings being taken every five minutes:

– Temperatures and relative humidity in at least 4 rooms.
– Carbon dioxide levels in the main living space.
– Window use (sensors showed if they were open or closed).
– Gas consumption (either the whole dwelling consumption or consumption by the gas fired heating appliance.
– Net heat to radiators (a practical proxy for Gross Space Heating in SAP).
– Net heat to water cylinder, net domestic hot water system output or in the case of the one house using a fuel cell; net thermal store output (all of which are a close proxy for Gross Domestic Hot Water in SAP).
– Electricity use covered within SAP – i.e. regulated energy:
  – Mechanical ventilation fans.
  – Lighting.
  – Heating circuit (which is a proxy for electricity use by Heat Pump plus Boiler Fan in SAP).
– Electricity use not covered within SAP – un-regulated electricity use:
  – Small power.
  – Kitchen circuit.
– Water consumption.
– Energy savings from four waste water heat recovery units.
– The relative humidity in four loft spaces.

Findings on ventilation and indoor air quality are the subject of Information Paper 6.

Image courtesy of Stewart Milne Group
AIMC4 homes at Portlethan, Aberdeen

Airtightness and Airborne Sound Test Results (Table 1)

Airtightness tests were undertaken, during the construction phase, on completion and after one year of occupation

The airtightness tests give an indication of the quality of design and construction (including the components such as doors and windows). All of the houses met their designed airtightness targets. The masonry homes tend to show the fabric getting tighter as the construction proceeds, whereas the timber constructed homes tend to get less tight. In both cases this is as expected. Masonry homes gather more layers with the application of drylining and timber frame and SIPs homes have more holes/openings made in the membrane and structure respectively. These findings show that, for volume production of homes, developers can be confident of achieving airtightness targets of 3-4 m³/h.m²@ 50Pa.

The airtightness results after a year of operation show either a slight deterioration of between 0.6 and 1.0 m³/h.m²@ 50Pa or a slight improvement of between 0.2 and 0.6 m³/h.m²@ 50Pa; the exceptions were the three open panel timber frame design which deteriorated by between 1.5 and 3 m³/h.m²@ 50Pa. These results on the open panel design may have been down to a different low cost airtightness strategy, which involved:

– the use of rigid insulation and the fitting and jointing of boards on site, which is inherently less airtight,
– the reliance on using only the foil on the insulation as the airtightness layer and no special tapes,
– the fitting of triple glazed windows on site (they were installed in the factory for the closed panel designs, which was easier).

Additionally the removal of testing equipment for monitoring the homes punctured the airtightness barrier and was not made good at the time of testing.

These results indicate that, with the exception of these open panel designs, any additional heat loss through the fabric over and above that which was anticipated in SAP is not due to the homes losing air-tightness to any degree during occupation. Any open panel designs used for this sort of specification in the future could use some of the techniques adopted by the closed panel designs to improve performance.

All of the AIMC4 homes performed well on airborne sound testing of party walls, reaching a level well above that required by Regulations and which would have accrued 3 or 4 of the credits available for this aspect of the Code for Sustainable Homes. Most of the occupants when interviewed having lived in the homes were satisfied with the performance of the party walls. There were comments from those living in adjoining properties on the Corby site that they could hear their neighbours but, as time progressed during the first year, they no longer saw this as a problem.

At occupant interviews the triple glazed units were reported as being effective in reducing noise from the outside environment. This decline in background noise may have had the unintended consequence of making occupants more aware of internal noise from their neighbours.

Table 1: Airtightness results and Sound performance of Party Walls

Location	Corby				Portlethan		Prestonpans			Preston			Epsom				
Fabric	thin-joint masonry				closed panel timber frame		closed panel timber frame			Sigma OP-4 Open panel timber frame			thin-joint masonry	SIPS			
					Sigma II	Sigma II Dynamic	Sigma II		Sigma II Dynamic								
	Detached	End-terrace	End-terrace	Attached	Detached	Detached dynamic insulation	End terrace	Mid terrace	End terrace dynamic insulation	End terrace	Mid terrace	End terrace	Detached	End terrace	Mid terrace	Mid terrace	End terrace
Airtightness m³/h.m²@ 50Pa																	
As-designed	4	4	4	4	4	3	4	2	3	4	3.1	4.2	4	3	3	3	3
Weather-tight					3.1	2.0	3.3	1.9	2.5				3.5	1.4	1.1	1.2	1.2
First Fix	6.0	4.2	6.2	8.2	3.7	2.5	3.8	2.6	3.6				2.7	2.1	2.5	2.1	2.1
Second Fix	5.3	5.6	6.0	6.8									2.6	2.0	1.9	1.8	2.1
As-built	3.5	3.7	3.3	3.6	4.2	3.8[3]	3.2	2.7	3.2	3.3	3.0	4.1	3.2	1.7	1.9	1.5	2.3
After one year of occupation	4.1	4.1	4.6	4.2	3.7	3.2	3.9	3.0	3.3	6.4	4.9	5.6	2.6	2.3	1.7	1.3	1.9
Airborne Sound Performance of party-wall $D_{nt,w} + C_{tr}$ (dB)																	
	54						Range 51-55			Range 51-55				51-54	52-55		54-57

Note: All test results other than those conducted at Corby and Preston are an average of pressurisation and depressurisation.

[3] Taken before opening made for ventilation holes in the walls for the dynamic insulation.

Heat Flux

The AIMC4 project was amongst the first to design and deliver homes requiring a "zero U-value party wall" as introduced into the Building Regulations (England & Wales) in 2010. A party wall is deemed to have a zero U-value when the cavity is fully filled and edge sealed.

The project undertook heat flux testing to three party walls in different homes and of differing constructions. This was to evaluate their thermal performance and to ascertain whether, in practice, they achieved a zero U-value.

As the homes were going to be subject to co-heating tests, it was not considered necessary to undertake heat flux testing to other building fabric elements, such as external walls, floors or ceilings. With the benefit of hindsight, a more comprehensive regime of as-built heat-flux testing would have been put in place. This would have included an increase in the array of sensors used in the party-wall tests to help improve statistical confidence and in the case of the masonry party-wall, to validate that results had not been unduly influenced by dabs.

The heat flux test results are shown in Table 2.

Although a very small sample and with only single point heat flux measurements on the ground floor and the uppermost floor walls, the results show varying performance.

Table 2: Party Walls - As-Built performance, Heat Flux Testing

Site	Party Wall Construction Type	Thermal U-value (W/K/m²)
Corby	Masonry	0.16 ± 26%
Epsom	Standard timber frame	0.05 ± 26%
Portlethan	Single skin timber frame	0.01 ± 26%

Little should be inferred regarding construction type as the results are a sample of one in each case. Two of the systems came close to achieving the design requirements, but none met the absolute target of having a zero U-value. This suggests that some party-wall heat loss may always arise and may well vary by construction method and house design. Further work is needed to explore this issue, by testing a greater sample of differing construction types and house/party-wall designs, and using a wider array of sensors to more accurately reflect whole wall performance.

This matter is further discussed with the aid of thermal images later in this report.

Describing the homes for the whole house heat loss (co-heating tests) and the post occupancy evaluation

A full description of the specification of the AIMC4 homes can be found in AIMC4 Information Paper 3. The descriptors used in this paper have been anonymised, to preserve privacy, so that comments and usage patterns cannot be traced back to specific homes and their occupants.

The nature of the fabric, i.e. whether closed panel timber frame, SIPs or masonry does not appear to have had a major impact on the energy performance of the homes (with the possible exception of one house – which will be discussed later). However, the ventilation and heat recovery strategies for air and water where they exist do appear to have made some difference and these elements are therefore described (see Table 3).

The homes with air-tightness specified to be less than 3m³/h.m²@ 50Pa in which mechanical ventilation with heat recovery (MVHR) was also specified, achieved the AIMC4 target (within SAP 2009) without the use of waste water heat recovery (WWHR). Where central mechanical extract ventilation (MEV) or intermittent extract fans (IEF) were used then waste water heat recovery was specified.

Table 3: Home Descriptions

Home	Ventilation strategy and presence/absence of WWHR
MEV1	MEV with manual boost control and WWHR
MEV2	MEV with manual boost control and WWHR
MEV3	MEV with manual boost control and WWHR
MEV4	MEV with manual boost control and WWHR
MEV5	MEV with manual boost control and WWHR
MEV6C	MEV with automated controls and WWHR.
MEV7C	MEV with automated controls and WWHR
DI1	Dynamic Insulation[4] Property with MEV and WWHR
DI2	Dynamic Insulation[4] Property with MEV and WWHR
IEF1	IEF and WWHR
IEF2	IEF and WWHR
IEF3	IEF and WWHR
MVHR1	MVHR (no WWHR)
MVHR2	MVHR (no WWHR)
MVHR3	MVHR (no WWHR)
MVHR4	MVHR (no WWHR)

[4] Further information can be found in AIMC4 Information Papers 3 and 6

Space heating: Whole House Heat Loss (Co-heating Test)

The co-heating test is a research tool designed to assess a buildings' overall "steady state" Heat Loss Co-efficient (HLC), arising from both conductive and infiltration heat losses through the building fabric.

The test involves heating the building to an elevated mean internal temperature for an extended period, usually 2 to 3 weeks, using electric resistance heaters. The heat loss co-efficient of the building is then calculated by analysing the data to determine the amount of electrical energy used to maintain the elevated temperature. As the test requires a sufficiently high internal/external temperature differential to be maintained (generally 10°C or more), this means that, in practice, the test can only take place during the colder months of the year.

In 2009, when it was decided to specify co-heating tests for the AIMC4 project, it was the general understanding that these tests would allow the heat loss co-efficient of the houses to be compared with reasonable confidence against both SAP and co-heating test results on other projects. This has subsequently been shown not to be the case.

Studies have shown that weather conditions, especially solar radiation can have a major impact on the accuracy and repeatability of the co-heating test[5,6] and this was reflected in the AIMC4 experience.

The tests were completed in accordance with a protocol developed and published by Leeds Metropolitan University, and whilst the protocol sets out a methodology for undertaking a test, it should be noted that there is no generally accepted protocol concerning the subsequent treatment of test data and presentation of results. Therefore different organisations undertaking tests are likely to adopt different approaches to the analysis (and in some cases the testing regime) as well as adopting differences in the way that the results are presented. For this reason great caution should be extended prior to comparing the results of any whole house heat loss (co-heating) tests with tests undertaken previously. Such tests are highly unlikely to be directly comparable unless the tests have been conducted, and the data has been both treated and presented, in an identical manner.

It is also not valid to compare measured results directly with those outputs from the original SAP calculations. The outputs have to be compared with some form of "corrected model" (see appendix for more information).

The AIMC4 tests and analysis were conducted by BRE Scotland and peer reviewed by Leeds Metropolitan University.

Ten co-heating tests were conducted on eight homes (the dynamic insulation homes were tested in both the static, fans off, and dynamic, fans on, states) on four different sites between January and March 2012. Four of the tests delivered data that is judged by expert opinion to be invalid as a suitable temperature differential could not be maintained and the solar gain was very large. Three of these were conducted in March 2012, which unfortunately was unseasonably warm and sunny.

The valid results are shown in Figure 2. They were conducted at different locations at differing times of the year, and with widely differing confidence levels in the results, so comparisons may be unreliable. The graph shows for the seven valid data sets the heat loss predicted by SAP, the corrected baseline model, the collected raw data and then the data corrected for weather and evaporation. These are in order of variance from the baseline model, starting with the least variance (for home DI2) on the left. The static tests show a heat loss of between 131% and 151% of the corrected model with the exception of home MEV6C which is 189%. The dynamic test gives a heat loss of 116% of the corrected model.

An important negative impact of the co-heating test is that, by its nature, it subjects a new home to accelerated drying out, whilst restricting ventilation. Normally a new home will take several months to dry out and equilibrate, depending on weather conditions and ventilation. All of the AIMC4 homes subjected to the co-heating test suffered cosmetic damage to interior fittings (skirting boards, doors, architraves, staircase strings etc.) where separation and, in some cases, warping occurred. In addition, there was mould growth in some properties. Considerable making good was required, as well as complete redecoration and deep cleaning.

Figure 2: Co-heating tests results showing the heat loss relative to the corrected baseline model

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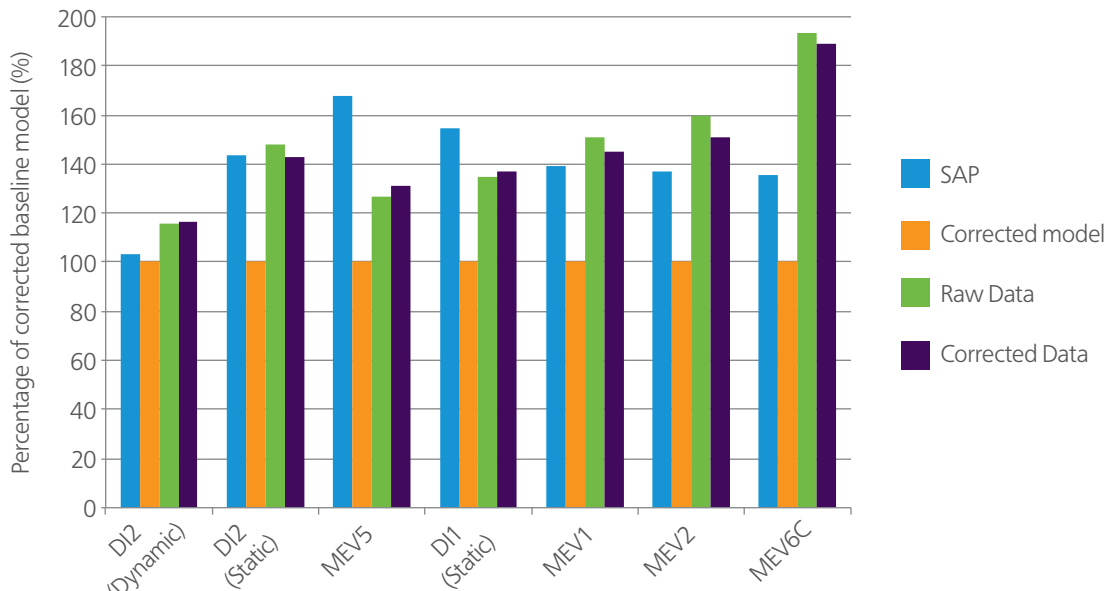
[5] Using simulated co-heating tests to understand weather driven sources of uncertainty within the co-heating test method, Stamp S, Lowe R, Altamirano-Medina H, UCL Bartlett School of Graduate Studies, delivered at the eceee 2103 summer study on energy efficiency, 3-8 June 2013

[6] Review of co-heating test methodologies (NF54), David Butler, Andy Dengel (BRE), NHBC Foundation, November 2013

# Space Heating: as measured in-use and the co-heating results

SAP produces an output of gross space heating. This cannot be measured in practice, but a close proxy is the heat energy sent to the radiators. Figure 3 shows this as a percentage of the SAP output, starting with the best performing household in-use to the left[7]. All the homes except one used more energy for space heating than predicted by the SAP model.

Although the co-heating test is measuring something different, it is interesting to make some tentative comparisons. The most obvious comparison with the co-heating results of Figure 2 is that most of the homes are indeed using more energy for space heating than shown in SAP, but the order of the results is not the same as the order of the output from the co-heating test. Home DI2, which in the dynamic test performed the best in co-heating, was the worst of the sample when it came to in-use monitoring. Homes MEV1, MEV2, MEV5 and DI1 are performing in the mid-range and do not differ widely one to another – although their performance is ranked differently between the two methods.

The opinion of the consortium is that the co-heating test was a poor predictor of the relative in-use space heating used by most of the homes. The performance of home MEV6C may be the exception to this; its co-heating result is the poorest when compared to the model and its

in-use performance is over twice that predicted by SAP. This is indicative of some underlying mismatch between the heat loss result calculated by SAP and the performance of the fabric of the dwelling, which is being picked up by the co-heating test and potentially confirmed by the in-use measurement.

Figure 3: Measured Space Heating Sent to Radiators as a percentage of Gross Space Heating Predicted by SAP
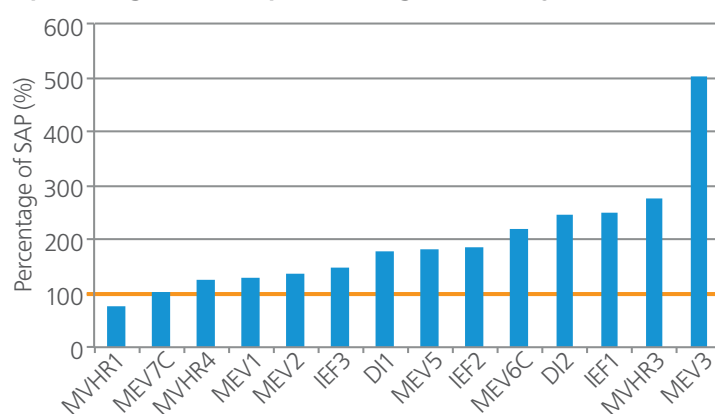
Space Heating: Analysis of the measured in-use results

One of the key pointers to how the homes are being used is the temperature in which they are being operated. This can be seen in Figure 4 (shown over) which shows the proportion of time that the temperatures of different rooms in the dwellings are within certain bands[8]. With the exception of the two houses on the bottom of the chart they are in the same order as Figure 3; i.e. the ones on the bottom of the chart use proportionally more space heating energy than the ones at the top. In the case of the two houses at the very bottom, no space heating data is available due to an equipment failure.

The most obvious observation to make when looking at Figure 4 is that, of those houses where results have been obtained for energy use, it is the hotter houses (those where the temperature range is more regularly over 25°C and less regularly under 18°C) that use more energy.

The extremely high temperatures worthy of note are:

– bedroom 4 in home DI2 which was being run at over 25°C for 25% of the time to compensate for excess air movement from the problematic dynamic insulation system. This made the room feel cooler from a thermal comfort perspective (for further discussion see the next section and Information Paper 6).
– the kitchen in home IEF1 (which peaked at over 35°C) and to a less extent the living room. Some of this may be driven by the very high unregulated small power usage (3303kWhr/year) and cooking.
– all the rooms in home MEV3, especially the lounge diner and,
– the lounge in home MVHR2 which is probably being warmed by heat emitting from the computer servers that the occupant is running in the under stairs cupboard (unregulated small power usage for this home was 4580kWhr/year)

Homes MEV7C and MEV2 both run their homes relatively cool, with the kitchens in each cases being below 18°C over a third of the time.

The project was also able to look at the percentage of time that a selection of the main windows and doors were open in the homes. The five homes using the least space heating when compared to SAP (76-136% of that predicted in the model) kept their windows and doors closed, only opening them 0.1-0.3% of the time between November and April (compared with 6.6% of the time for the high energy use of home IEF1).

It also appears to be the case that homes MVHR1, 3 and 4 tend not to cool down below 18°C. This is not a thermal mass effect, as these homes have a relatively low thermal mass. It is therefore likely that this is a combination of the relatively good airtightness (preventing outside infiltration of cold air), the fact that all three keep their windows closed during the winter (0.1-0.3% of the time between November and April) and that the MVHR systems are recycling space heating and heat gained from showering and bathing activities. Home MVHR2 behaves differently with bedroom 1 in particular cooling down, but the windows in this house are open 1.8% of the time between November and April. The loss of temperature data for July and August for these houses, due to a technical fault, prevents any analysis of what is happening at the other end of the temperature scale and skews the temperature results for these properties.

How the homes are used is the overwhelming driver in their energy consumption. This can be clearly seen in homes IEF1 and IEF 3, which are both near identical end terrace homes, built in the same terrace, but with completely different energy use profiles.

When interviewed, all sixteen sets of monitored occupants were satisfied with the temperatures in their new home in comparison to their previous home.

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[7] Of the seventeen AIMC4 homes, sixteen were monitored and of these two had problems with collecting the space heating data. These two are home MEV4 and home MVHR2 which are shown at the far left hand end of the graph.
[8] Of the seventeen AIMC4 homes, sixteen were monitored.

Figure 4: Percentage of measured time that the homes are within the temperature ranges (note that no temperature data was collected in Homes MEV7C and MVHR1-4 in July and August).
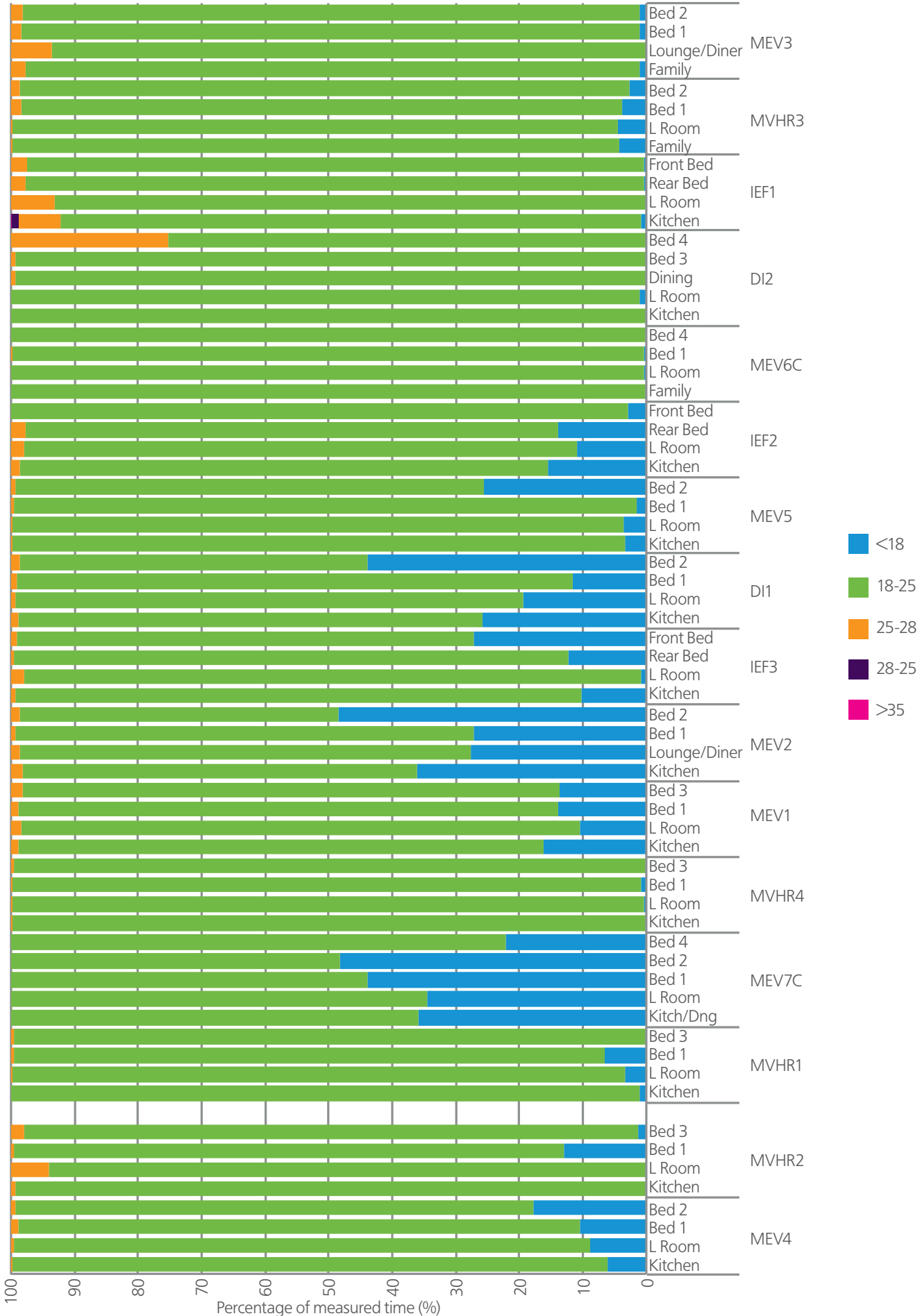
Space Heating: commentary on specific homes

Homes MEV3 and MVHR3

Due to equipment failure only three mid-terrace homes were monitored and it is interesting to note that the two households using proportionally the largest amount of energy when compared to SAP both live in mid-terrace homes. There are four possible reasons for this:

1. SAP calculates very low energy requirements for the space heating of terrace homes, especially small ones such as home MEV3. If a household uses more heat than anticipated this appears to be larger in proportion to the SAP calculation when comparing with a bigger house, with a larger designed heat demand.

2. Mid-terrace homes have relatively little external fabric to floor area and as much of this fabric has proportionally more penetrations, they are more sensitive to any design, energy modelling or construction shortcomings (see Figure 5).

3. The "zero U value party walls" may still be a point of weakness (see Figure 6 and Figure 7). These homes were based in Corby and Epsom where the heat flux tests (see Table 2, page 7) suggest that further research is required on the performance of these walls and the mechanisms of potential heat loss

4. They might be losing heat through to neighbouring properties – this would be the case even with a perfect "zero U-value wall", if there was a temperature differential between the properties. This is particularly relevant to home MEV3 which is flanked by homes MEV2 and MEV4, both of whom run their properties cooler.

Specifically with regard to home MEV3 we do know that the rooms are rarely below 18°C and, in fact, that they are more often above 25°C. The occupants do not open the windows excessively in winter, so this does not explain the amount of heat that they are consuming. However, they did experience problems operating their heating system and never used the energy display device installed in their home. It may therefore be the case, that they are heating the property more than required during the warmer months of the year.

Despite this the occupants of home MEV3 described themselves as generally satisfied with their energy bills.

When looking at home MVHR3, a similar thermal image to Figure 6 can be seen in Figure 8.

The occupants of home MVHR3 are very similar to those in home MEV3 in that they were not comfortable in operating the heating system. They did not use the thermostatic radiator valves or the energy display device. This is consistent with them being the only household in the study who said that they were not aware of how to live a sustainable lifestyle.

They rarely open their windows in winter, so this is not a big driver of heat loss, but they may again be using the heating too much in the warmer months. The loss of data for this property in July and August does frustrate any potential analysis in this area. However in interview the occupants reported high summertime temperatures.

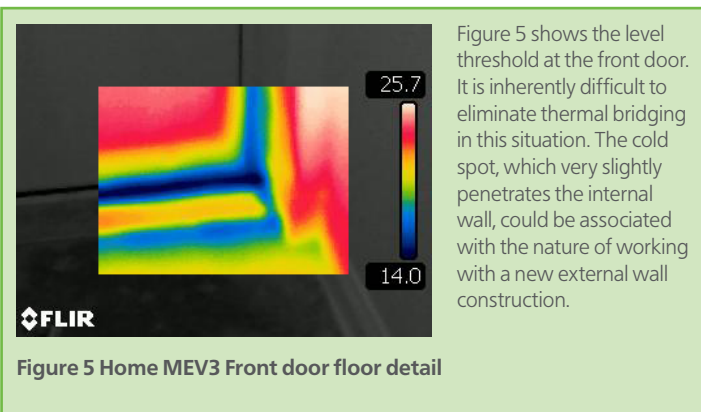They too described themselves as generally satisfied with their energy bills.

Figure 5 Home MEV3 Front door floor detail

Figure 5 shows the level threshold at the front door. It is inherently difficult to eliminate thermal bridging in this situation. The cold spot, which very slightly penetrates the internal wall, could be associated with the nature of working with a new external wall construction.
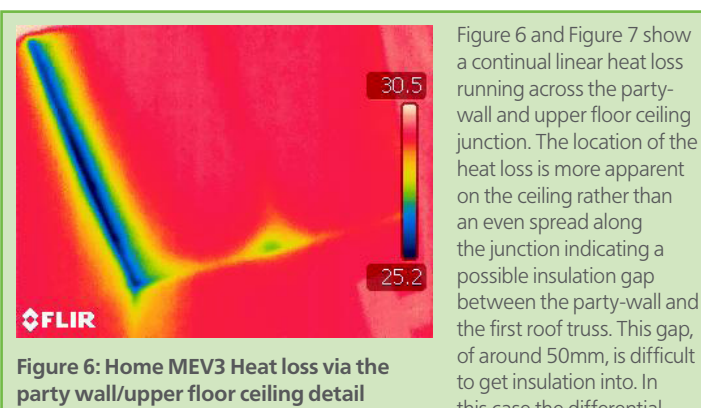

Figure 6: Home MEV3 Heat loss via the party wall/upper floor ceiling detail

Figure 7: Home MEV3 Heat loss via the party wall/upper floor ceiling detail

Figure 6 and Figure 7 show a continual linear heat loss running across the party-wall and upper floor ceiling junction. The location of the heat loss is more apparent on the ceiling rather than an even spread along the junction indicating a possible insulation gap between the party-wall and the first roof truss. This gap, of around 50mm, is difficult to get insulation into. In this case the differential of around 4°C may show that at least part of the heat loss shown in the heat flux test could be due to air circulating behind the plasterboard being driven by the lack of insulation at this point. Further research is needed to understand this. Meanwhile the developers have refined their site inspection regime to ensure this gap is always insulated, where possible by making it larger so that it is easier to fill.
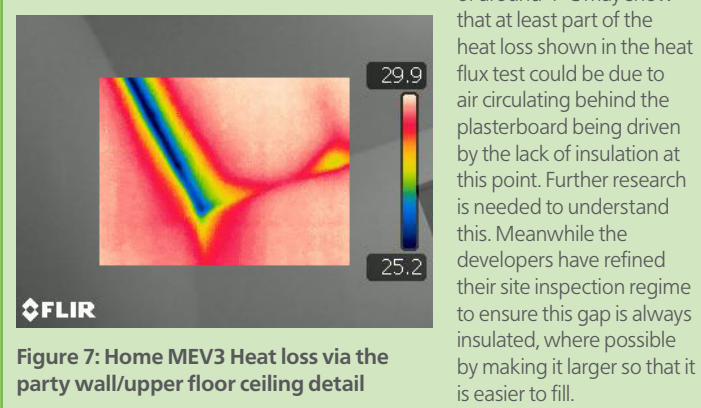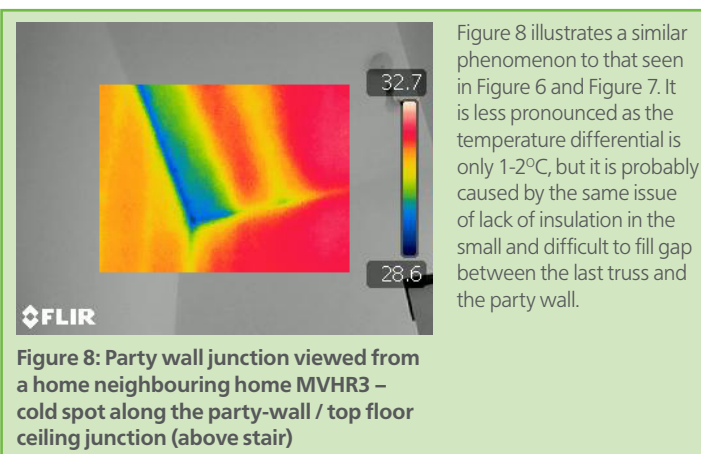

Figure 8: Party wall junction viewed from a home neighbouring home MVHR3 – cold spot along the party-wall / top floor ceiling junction (above stair)

Figure 8 illustrates a similar phenomenon to that seen in Figure 6 and Figure 7. It is less pronounced as the temperature differential is only 1-2°C, but it is probably caused by the same issue of lack of insulation in the small and difficult to fill gap between the last truss and the party wall.

Home IEF1

The way in which the home is used is likely to be the overriding factor for home IEF1. The thermographic images from this row of terraces did not highlight any particular issues for this home, but a neighbouring plot showed the same sort of party wall junction issues as highlighted in Figure 6, Figure 7 and Figure 8 and also a problem in respect of insulating the eaves that was seen on other AIMC4 homes (see Figure 9 and Figure 10).

As mentioned earlier home IEF1 is operated at elevated temperatures with the rooms rarely below 18°C and more often above 25°C. Additionally, the windows are open more often in this AIMC4 home than any other during the period of November to April (6.6%). The occupants on interview said that they were not interested in environmental issues, they never used the energy display device and they did not know how to minimise running costs.

Home DI2

Home DI2 is a detached house. The relatively poor space heating performance is probably due to issues around dynamic insulation and the way in which the house is used by the occupants.

The occupants run the house hot, but this is in part to compensate for the air movement generated by the operation of the dynamic insulation which makes some parts of the home feel cooler. This is particularly the case in bedroom 4, which is 25% of the time above 25°C. Remedial work to the house was necessary to increase the radiator capacity in this room to overcome the issues caused by the air movement. This is an interesting example of unintended consequences while trialling new technology and much can be learnt from the experience.

The effect of the dynamic insulation is shown in the thermographic images along with some other fabric issues (see figures 11, 12 and 13).

The occupants of home DI2 have said that they are not interested in environmental issues and that they have never used the energy display. This is probably a factor in their high energy usage.
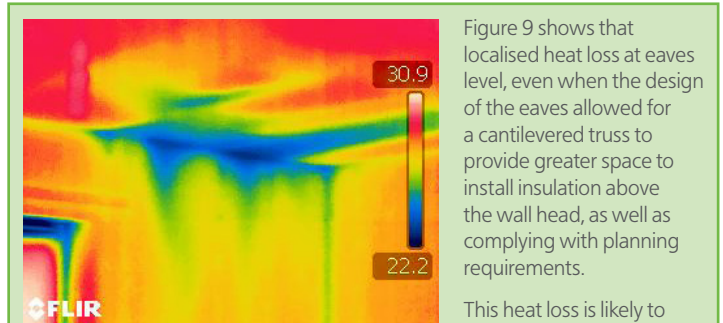
Figure 9: Front bedroom external wall / ceiling junction

Figure 9 shows that localised heat loss at eaves level, even when the design of the eaves allowed for a cantilevered truss to provide greater space to install insulation above the wall head, as well as complying with planning requirements.

This heat loss is likely to be caused by either the solid timber header beam or air movement around the eaves area (where loft insulation does not always reach the eaves point).
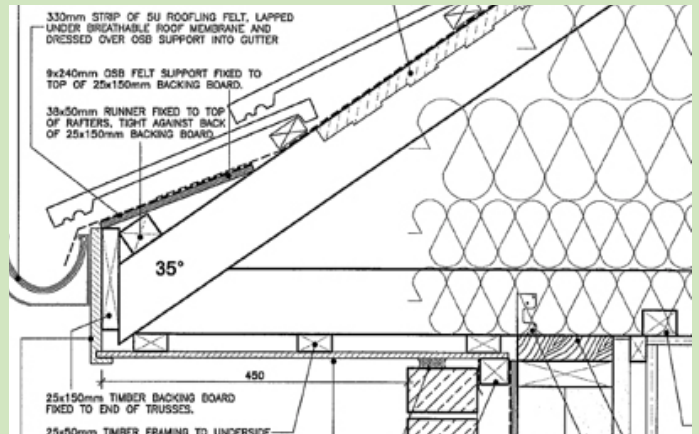

Figure 10: Eaves design detail

Figure 11: Living room dynamic insulation supply louvre in external wall and heat loss around French doors

Figure 11 shows two issues. The first is the incoming air from the dynamic insulation louvre. The photo has been taken during the co-heating test and the louvre is bringing in air at around 21°C, but the walls are at around 30°C (which does not reflect in use conditions) .

The second issue is the poor seal around the French doors. These may have been installed out of square, but it is more likely that they have dropped or twisted through their own weight, as they are triple glazed. This issue was seen in some other large windows on a mixture of AIMC4 sites.

Figure 12: Cold spot on external wall

Figure 12 shows a cold spot within the dining room. Behind this, there is a recessed external gas meter housing which requires a penetration through the external closed panel wall. Although the detail shows external sealant and insulation, it is possible that one or the other (or both) has not been followed. This has resulted in a localised thermal weak spot (or air movement) around the conduit penetration.

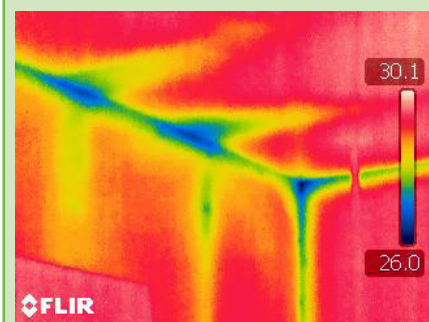As a result of identifying this problem changes have been made to the developers quality assurance procedures.

Figure 13: Heat loss from guest bedroom adjacent gable wall

Figure 13 indicates heat loss within the ceiling below the roof space. The cold areas suggest possible ingress of cold air beneath loft insulation. This is likely to be as a result from the complexity of fitting ceiling insulation in this area.

The roof is insulated with four layers of insulation and an air membrane. The area has a complex structural layout, including a valley to gable/eaves roof arrangement. It is likely that insulation has not been tightly fitted to the underside of the ceiling membrane or timbers.

In addition, there is thermal bridging where the service cavity battens run parallel with the truss timbers. This junction is not required to be accounted for within SAP.

Home MEV6C

Home MEV6C performed the poorest in the co-heating test. It is one of the more complex AIMC4 home designs, presenting challenges with an integral garage (including access door), footprint complexity, bay windows and external recesses (for example by the front door). It was constructed using closed panel timber frame. A detailed analysis of the thermal bridging highlighted eleven junctions unaccounted for in SAP, representing an additional 20% (59m) of additional linear thermal bridging heat loss, and estimated to account for 15% of the measured heat loss from the co-heating test. Some of this can be seen in the thermal images (see figures 14, 15, 16, 17, 18 and 19).

Additionally, the occupants have kept the rooms warm, rarely below 18°C and more often above 25°C.

Figure 18: Heat loss around front door entrance

Figure 18 shows the entrance recess, which is approximately 900mm deep with relatively slender returns to work in and with internal partition layouts and external coursing. As a consequence, the corner arrangements have a higher than normal amount of timber studs. The floor above extends over the top and is supported on an arrangement of timber joists within the floor zone. This is further complicated by the inclusion of stairwell trimmers from the stair void opposite the entrance. As a consequence there are many timbers, resulting in a hard to insulate area and increased levels of thermal bridging.

A similar problem is occurring at the inverted corner of the bay window.

Figure 14: Heat loss at unheated integral garage ceiling to external wall junction

The junctions and construction details around the head of the integral garage walls present a thermal bridge (Figure 14). The detailing (Figure 15) is complex as the ground floor external walls on two sides are 90mm timber frame un-insulated wall, supporting a wider 195mm wall above to the main home, which is well insulated. This results in additional timbers within the floor zone and a restriction on available space for insulation.

The thermal bridging is not accounted for in SAP.
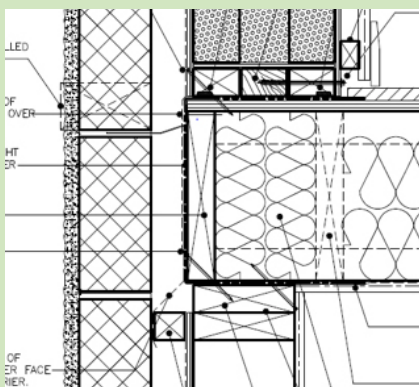
Figure 15: Construction details
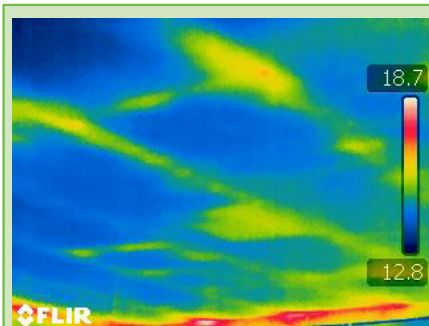
Figure 16: Heat loss through integral garage ceiling.

Figure 17: Integral garage ceiling during second fix

Figure 16 shows heat losses from the living space above the integral garage, through the floor zone. The floor contains a complex arrangement of plumbing works relating to hot water and heating feeding the en-suite above and rising from the boiler located in the garage (see Figure 17). This resulted in hard to insulate areas within the floor zone.

An additional heat loss is showing at the head of the wall around the un-heated garage. This is an unaccounted for thermal bridge as it is not specified with SAP Appendix K.

The thermal bridges from the ducts are also not accounted for in SAP.

This analysis has resulted in consideration being given to changing both insulation design and site quality assurance practices associated with integral garage homes.
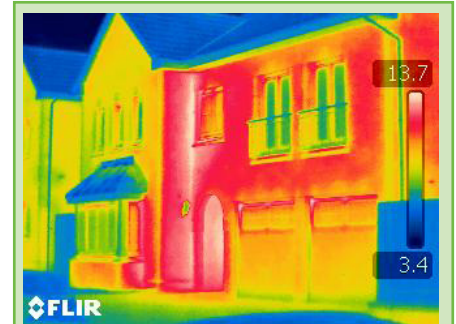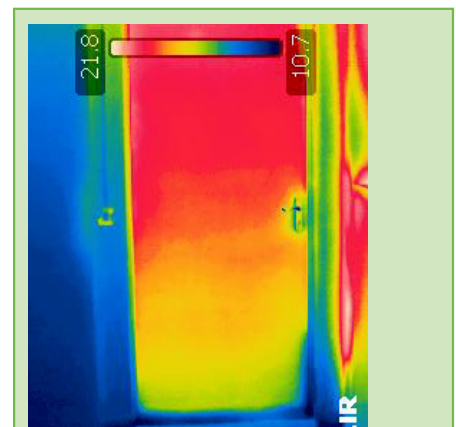

Figure 19: Heat loss via internal access door to integral garage

Figure 19 indicates strong temperature contrasts covering quite a large area suggesting significant heat loss. The integral door between the garage and utility room is an un-insulated solid core internal fire door. The U-value of the fire door is 2.0. This is not a design versus as-built performance issue as this was known at the design stage and accounted for in the SAP model. The utility space helps buffer the heat loss and forms a sheltered space, between the kitchen and garage, which is infrequently occupied.

Changes in door specification are being considered that meet fire requirements but with improved thermal insulation.

Home MVHR1

MVHR1 was the only home that used less space heating than predicted by SAP. The occupants are particularly environmentally aware. They were the only people who said that the environmental features of the house were **very** important to them. All the rooms were less than 25°C for 99% of the time (no data was available for July and August) and the windows were rarely open in the winter.

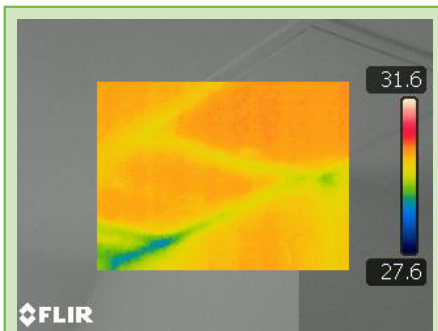The thermal imaging shows a very good standard of fabric build:

Figure 20: Loft hatch

Figure 20 shows a very well insulated loft hatch opening. The insulation goes all the way to the opening and the seal is good. This was not the case in all AIMC4 homes and through this work new hatches have been sought that provide an improved seal.
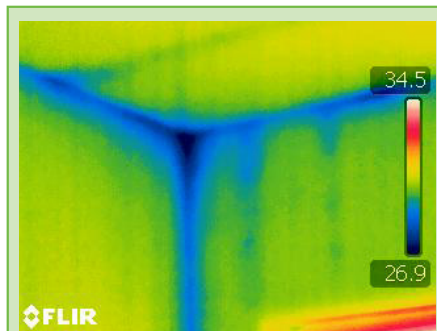
Figure 21: showing slight cold spots along the

(i) party wall / second storey ceiling junction (to the top left of the image) and

(ii) front elevation external wall and second storey ceiling junction (to the top right of the image)

Figure 21 shows only around a 1°C difference in temperature at the interface with the party wall and ceiling junction.

Image courtesy of Barratt Developments Plc. AIMC4 homes at Corby

Water Heating

As with space heating, it is not possible to measure directly the water heating shown in SAP. What has been measured is either net heat to the hot water cylinder, net heat from the domestic hot water system output (where there is no cylinder) or in the case of one house where a fuel cell was used, net heat from the thermal store output. These measurements have been normalised to compare them with SAP by dividing by the number of people actually in the house and multiplying by the number of occupants used in SAP (which assumes a direct linear relationship between the number of occupants and the hot water use). The results when compared to the SAP prediction are shown in Figure 22[9].

If the total water consumption is divided by the number of occupants per house in the SAP model, this produces Figure 23[10]. By comparing Figure 22 and Figure 23 it is possible to see that there are some links: The three largest users of energy for hot water, homes DI2, MVHR4 and IEF1 are amongst the four biggest users of water. Home IEF3 had excessive water use due to a water leak external to the property which took some time to resolve. The lowest user of energy for hot water, home IEF2 is also the lowest user of water.

Figure 22: Measured Water Heating (normalised) as a percentage of Gross Domestic Hot Water Shown in SAP
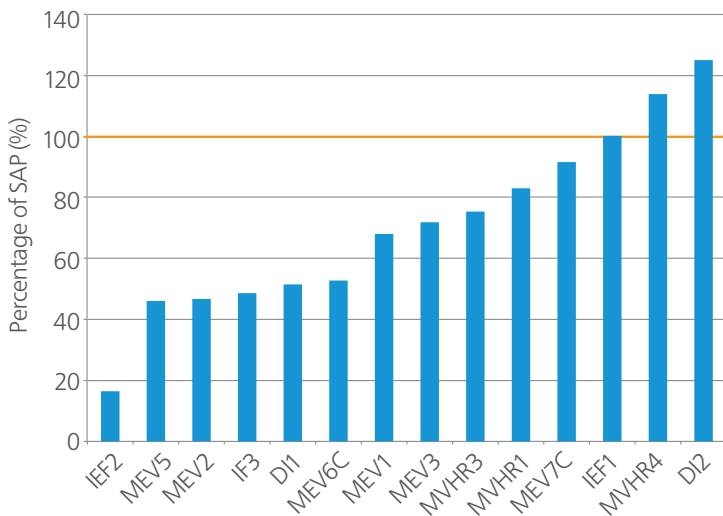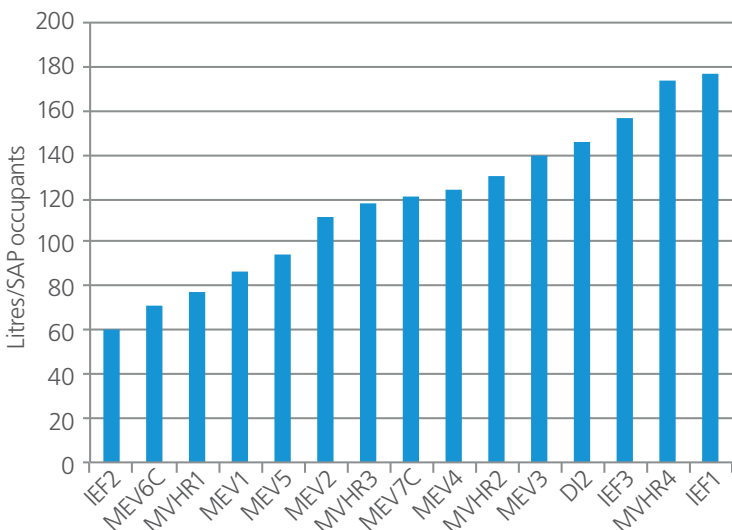

Figure 23: Water consumption per person in SAP

With the exception of three homes all the properties used less heat for hot water than would be expected from SAP.

When interviewed about hot water provision the occupants on the whole described their experiences as positive with only one, MVHR4 experiencing problems. The heating and hot water in this property was uniquely provided by a fuel cell which was installed for the first time in a new build home. Some issues with hot water supply took time to resolve. It is also worth noting that the occupants of home MVHR4 were the second highest users of water in Figure 23. This high water use contributed to the problems with hot water supply via the fuel cell.

Waste Water Heat Recovery (WWHR)

As part of the project the in-use performance of waste water heat recovery units were measured, but due to monitoring equipment failures, only two full sets of results were collected (see Figure 24).

The two cases show extensively more savings than would be expected from SAP. In the case of home MEV7C, the WWHR unit is calculated to give a low saving because the shower in the en-suite to the master bedroom is fitted over a bath.

Energy savings from WWHR can be displayed as a percentage of the total hot water calculated/used (see Figure 25).

This shows that for home MEV3, 25% savings were calculated, but 35% were obtained and for home MEV7C, 15% were calculated and 41% were obtained.

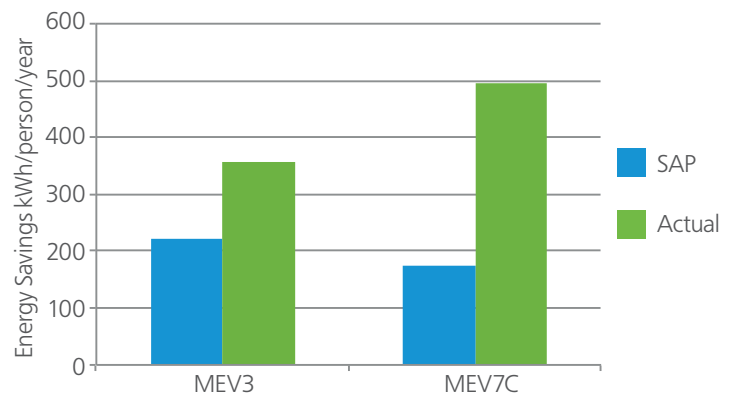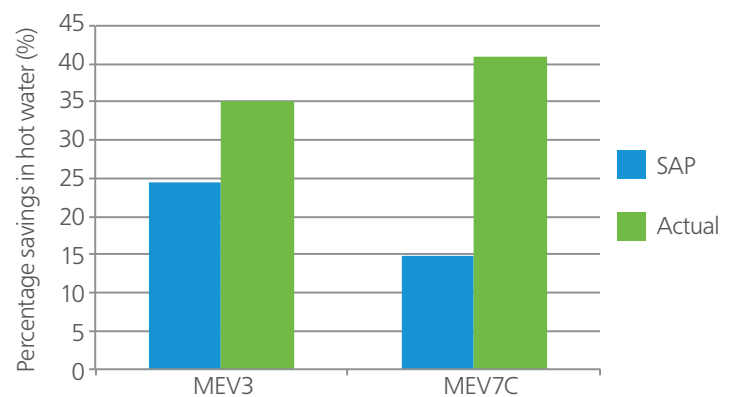**Figure 24: Savings from waste water heat recovery per person**

**Figure 25: Percentage saving shown in SAP and actual for WWHR**

[9] Of the seventeen AIMC4 homes, sixteen were monitored and of these two had problems with collecting the water heating data.
[10] Of the seventeen AIMC4 homes, sixteen were monitored and of these one had problems with collecting the water usage data.

On looking at water heating energy savings per person relative to those indicated by SAP (see Figure 26) it is interesting to note that the eight best performing households, who were all using at least 257kWhr per person per year less energy than shown in SAP, all had WWHR.

Figure 26: Water heating energy savings per person over those shown in SAP
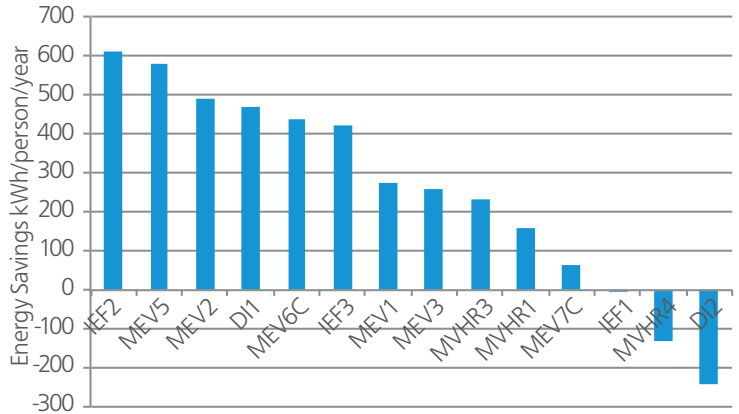
Regulated Electricity Use

SAP shows electricity use for ventilation fans, the heating pump, the boiler fan and lighting. Lighting and ventilation fans can be directly measured. The heating circuit can be measured and this can be used as a proxy for the heating pump plus the boiler fan.

The results are shown in Figure 27, which compares actual measured usage with the SAP results[11].

All but one household used less regulated electricity than calculated in SAP, with 11 out of 14 using 73% or less.

The best performing household, home MEV2, used only 61kWh of electricity for the heating circuit in comparison to SAP which showed 175kWh. As the house was kept relatively cool it is fair to speculate that the circuit was using less power than anticipated by SAP. This household also used only 34kWh of electricity for lighting instead of the 364kWh shown by SAP.

At the other end of the scale the worst performing household, home DI2 used 856kWh to light their house instead of the 555kWh shown in SAP and this was because they changed their light bulbs away from low energy ones after occupation. They also used more electricity for the heating circuit than predicted.

Homes MEV3 and MEV7C also had relatively high light usage (when compared to the other AIMC4 homes), with home MEV3 using 344kWh where SAP showed 316kWh and MEV7C using 362kWh where SAP showed 496kWh.

Homes DI2, MEV3 and MEV7C all used less electricity to run the ventilation fans than SAP showed, but the otherwise low electricity user, home MEV2, used more. This will be discussed further in Information Paper 6.

Figure 27: Regulated Electricity use as compared to SAP

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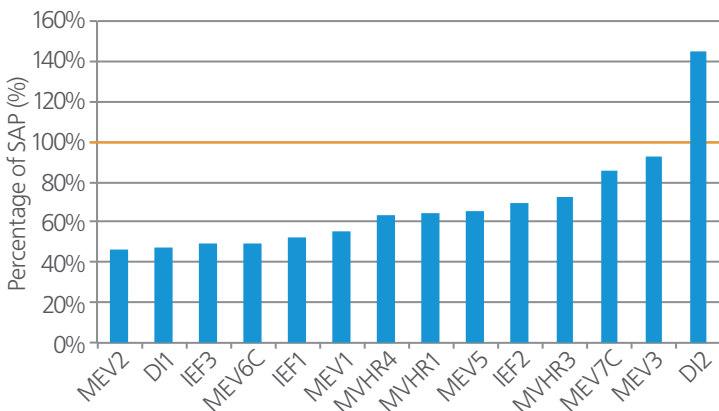
[11] Of the seventeen AIMC4 homes, sixteen were monitored and of these two had problems with collecting the electricity use data.

Problems with Measuring In-use Performance

It is worth noting that significant practical problems were experienced with measuring the in-use performance of the homes.

There were multiple failures of the measuring equipment despite all being purchased new with manufacturers' warranties, and bought on quality specification, not lowest price. The failures resulted in occupants having to be disturbed (sometimes on several occasions) for these items to be replaced.

The data hubs relied on a robust mobile signal and when this was not available some data was lost, although normally not enough to be critical.

There was, however, a separate failure for five data hubs during the summer period, which lasted for two months, due to a failed component. Significant delay was experienced in obtaining a replacement from the supplier.

Additionally data for space and hot water heat usage was corrupted on two of the dwellings, along with WWHR data on two more, due to issues being encountered with the installation and use of heat meters. Water usage was unable to be collected on one property, as it was sold too late to install the meter.

Data loss through monitoring equipment failure is very frustrating and represents a considerable financial loss of invested research capital, which dwarfs the not inconsiderable cost of the equipment. Monitoring equipment must be designed to be more reliable, and have back-up systems to support loss of mobile signal where this has to be used. In addition self-monitoring and error reporting is essential.

Conclusions

Figure 28 shows the measured in use regulated energy for the homes, compared with SAP, with SAP being 100[12] (water heating has been normalised to account for occupancy).

The overall results for regulated energy consumption for the fourteen dwellings, were that:

– five of the homes were within ±10% of the SAP result,
– four homes used less energy than SAP; 76-86% and,
– five homes used more; up to 196%.

This correlation with SAP is matched by the experience of the occupants when asked about their energy bills; with fifteen out of sixteen saying that they were satisfied with their bills and one being neutral because they could not tell, as their previous house had been smaller.

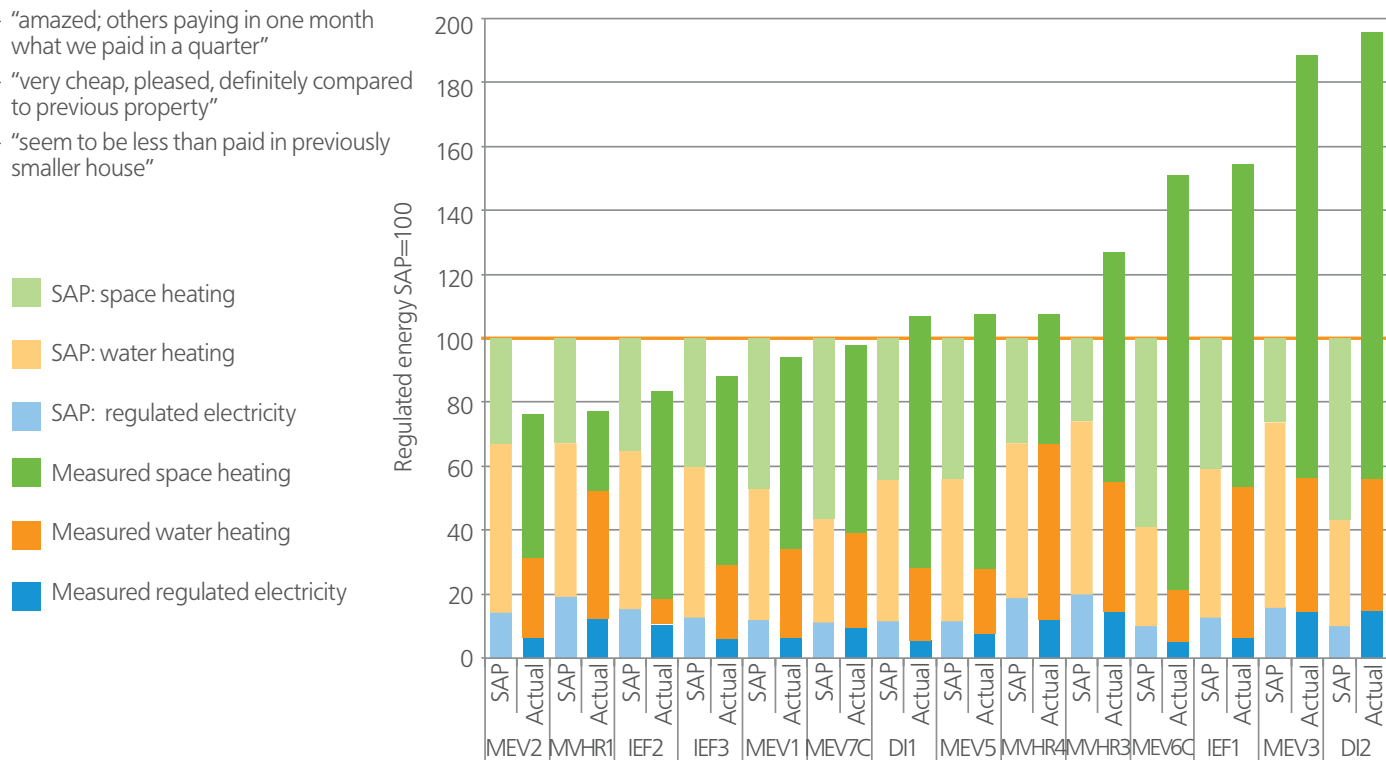Some of the comments from the occupants were:

– "payments less than previous property"
– "amazed; others paying in one month what we paid in a quarter"
– "very cheap, pleased, definitely compared to previous property"
– "seem to be less than paid in previously smaller house"

An analysis of the running costs will be shown in Information Paper 7.

There were problems with the dynamic insulation properties, particularly at the beginning of occupation, with controlling perceived temperature and ventilation. This had appeared to ease towards the end of the first year of occupation; although it had been necessary to increase the size of one of the bedroom radiators and to change some of the vents over to trickle vents in home DI2 (see Information Paper 6).

Overall the interviews in general reveal occupants who are happy with the internal environment of their homes and feel that they can control their comfort levels and optimise their homes for energy efficiency.

Figure 28: Measured Regulated Energy Use (water heating normalised for occupancy levels) and Predicted SAP energy use (SAP=100)

Legend:
- SAP: space heating
- SAP: water heating
- SAP: regulated electricity
- Measured space heating
- Measured water heating
- Measured regulated electricity

[12] Of the seventeen AIMC4 homes, sixteen were monitored and of these two had problems with collecting energy use data.

Lessons Learned

The occupant experience

– The occupants find that the AIMC4 homes are comfortable and pleasant to live in with no indications of any health or additional maintenance issues.

– The occupants are overall satisfied with their fuel bills.

– The majority of occupants (nine out of fourteen) have an overall in-use performance better than or equivalent to SAP.

– How the occupants use the homes is a major driver for their performance. This can have a larger impact on energy usage that the low energy design features of the homes.

SAP and its use

– In the AIMC4 homes SAP is under estimating the energy required for space heating. This is probably due to:

  – the absence of some thermal bridges (some of which are being added into SAP 2012),

  – that the U-values and Psi-values calculated using the methods in BR443[13] and BR497[14] are overly optimistic (as suggested by the Zero Carbon Hub[15]) and,

  – underestimating heat loss at party walls

  – SAP applying standard occupancy patterns and defined temperature conditions.

– Further research is required on "zero U-value party walls" to understand their effectiveness, and design and construction issues.

– In the AIMC4 homes SAP is over estimating the hot water requirement and this appears to be, in part, due to under estimating the savings from waste water heat recovery. Further research is required to establish whether the waste water heat recovery is being modelled appropriately within SAP.

– In the AIMC4 homes SAP is over estimating regulated electricity consumption and this is clearly worth reviewing.

Design and Construction

– Special consideration should be given to the robustness of some details where it is difficult to install insulation; such as eaves, bay windows, level thresholds or the gap between the last truss before a party wall and the party wall itself.

– For volume production developers can be reasonably confident of achieving airtightness targets of 3-4 m³/h.m²@ 50Pa

– The thermal imaging highlights areas where construction processes and quality assurance procedures can be improved. All the developers have changed some procedures and/or products as a result of AIMC4 and one is now regularly checking homes using a thermal imaging camera.

– AIMC4 has highlighted areas for improved quality assurance procedures.

Products

– The triple glazed uPVC windows have performed well, but research is required to ensure that seals on the openings are maintained overtime as the weight of the glazing units increases the risk of dropping or twisting.

– WWHR is operating effectively.

– Not all loft hatches used in AIMC4 sealed well and this resulted in new ones being sourced and developed.

– Personnel doors for integral garages should be sourced for energy performance, as well as fire performance.

Testing

– The co-heating test is unsuitable for large-scale application across the house building industry due to:

  – the difficulties in establishing a steady state,

  – the lack of agreed methodologies for the test and for data analysis,

  – the length of time required for the test,

  – the fact that it can only be conducted in the winter months and

  – the damage that it causes to the homes.

  It does have merit as a tool to inform research and development[16].

– Heat flux testing does require readings to be taken at more positions than was the case in AIMC4 to give more confidence in results.

– In-use measurement has many merits, but there is a need for more reliable, robust and cost effective equipment.

– Consideration should be given by developers to more widely using thermographic images as part of their quality assurance processes.

– The post occupancy interviews gave many useful insights.

Image courtesy of Stewart Milne Group
AIMC4 homes at Prestonpans

[13] Conventions for U-value calculations (BR 443, 2006 Edition)
[14] Conventions for Calculating Linear thermal transmittance and Temperature Factors (BR 497)
[15] Closing the Gap Between Design and As-built Performance, Evidence Review Report, March 2014, Zero Carbon Hub
[16] Closing the gap between design and as-built performance – new homes, Interim Progress Report, July 2013

Appendix: BRE Scotland's Analysis of the Co-Heating Data and the development of the Baseline Model

The As-designed Baseline Model and SAP

In order to evaluate the as-built test performance it is necessary to develop an appropriate as-designed baseline. The starting point for such a comparison is not the SAP model as normally used, because SAP uses standardised internal conditions, external weather parameters, etc. A steady state "corrected" thermal model is developed using the same basis as SAP and which more accurately represents the building and the specific conditions under which it was tested.

Corrections applied to the test data / and to the thermal model

During analysis of a co-heating test it is common to apply a number of correction factors to account for certain external effects. A correction for solar gain was applied to the raw collected data, as is normally the case, and an additional correction was also applied to account for the energy attributable to evaporation of moisture within the properties. A correction was also applied to the thermal model to account for the impact on infiltration heat loss as a result of the actual air-tightness levels and the actual wind speed.

This series of corrections are applied to attempt to account for the non-steady state test environment of the homes. Details of the corrections applied to the data from the AIMC4 homes are:

Correction for solar gain

The findings from the research have shown solar gain corrections can result in an adjustment of up to 44% of the measured value of the Heat Loss Co-efficient. Solar gain corrections have been derived from either site solar measurements or estimated in accordance with BREDEM-8 solar data[17] collected from weather stations in the surrounding area.

The use of BREDEM-8 data as opposed to site measurement was considered as a possibility when looking at whether co-heating tests might become more widely adopted, as it saves on the installation of a local weather station being physically attached to the home.

The large solar corrections that were used were applied to those homes that were tested in March 2012. This month was unseasonably warm and sunny, with external air temperatures exceeding 20°C over an extended period. High levels of solar gain were also experienced at this time. The combination of these effects resulted in three tests delivering data that is judged by expert opinion to be invalid as a suitable temperature differential could not be maintained and the solar gain was very large.

Correction for air moisture levels inside the home

BRE Scotland corrected the Heat Loss Co-efficient for the energy used to evaporate moisture in the air within the home. This moisture can present itself from either the drying out of the fabric and finishes and/or from moisture contained in the air entering the home via infiltration (air leakage). To compensate for the power input to evaporate moisture the measured heat losses were corrected by factors of between 2% and 10%.

Several of the homes were built and/or tested during periods of heavy rainfall and in most cases were tested very soon after internal finishes were applied and it was not possible to allow time for the homes to dry out between completion and testing. This was particularly the case on one site that had to be completed in January- February, to fit in with the co-heating test requirement for a cold weather window.

Correction for infiltration due to actual air-tightness and actual wind

All the homes were subject to wind effects generating differing levels of impact subject to direction and speed which, in turn, affect the building envelope performance. Additionally, the thermal model requires the actual as-built air-tightness levels to be input. The resultant corrections on the design Heat Loss Coefficients ranged from 4% to 19%.

Co-heating tests for dynamic insulation properties

The properties with dynamic insulation were tested in two ways:

– with the ventilation system not operative and the vents sealed – a static test.

– with the ventilation system operative– a dynamic test.

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[17] BREDEM-8 is the current monthly version of the BRE Domestic Energy Model. The model estimates energy consumption in dwellings. The solar algorithm within the model accounts for differences in solar levels as a result of site latitude and time of year. The principles behind the model are discussed and the equations are listed in the BREDEM-8 publication; "BREDEM-8: Model Description, 2001 Update, BR439"