Confirming the effectiveness of insulation upgrades applied to Glasgow housing

Final report to Glasgow City Council

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24 August 2015

0. Preamble

The ESRU group at the University of Strathclyde was contracted by Glasgow City Council (GCC) to develop a low cost procedure for the assessment of insulation upgrades when applied to social and private sector housing throughout the City. The project, undertaken as part of the Glasgow Future Cities Demonstrator funded by the Technology Strategy Board (TSB, now Innovate UK), comprised the monitoring of a representative sample of 49 upgraded dwellings, with site visits and modelling studies used to undertake assessments and extrapolate beneficial outcomes to the entire housing stock. This report describes the project aims and method, and presents outcomes from the monitoring and modelling activities.

1. Project aims

The project set out to test 4 hypotheses as follows.

- That sensors can be deployed in dwellings to enable a low cost and rapid confirmation (or otherwise) of the efficacy of insulation upgrades.
- That citizens will accept the imposition of short-term indoor monitoring in return for useful feedback or remedial action where appropriate.
- That future housing insulation upgrades will benefit from mandatory monitoring applied to a representative sample of the estate being targeted.
- That the quality assurance of insulation upgrade programmes can be supported by the existence of openly available evidential case studies.

These hypotheses were examined in relation to dwelling insulation upgrades undertaken within 8 Glasgow districts: Shettleston, Pollokshields, Carntyne, Mosspark, Shawlands, Drumchapel, Yoker and Anniesland.

2. Glasgow City

Based on an analysis of the Scottish House Condition Survey Local Authority Tables 2012, and Scottish Neighbourhood Statistics for 2011, Glasgow has around 272,000 dwellings of which around 110,000 (40%) are socially owned and, of these, 44,000 (41%) have no wall insulation and are in the hard-to-heat category:

- 16,000 are pre-1919 solid walled traditional construction;
- 4,000 are inter-war or 1940s solid walled;
- 24,000 have cavity walls that in practice cannot be insulated easily (early types, inter-war and just after) because the cavity is rubble filled or difficult to access (e.g. in tenements or high-rise buildings).

It is reasonable to assume that in social housing cases where cavity filling was straightforward, this form of insulation upgrade has already been carried out by the housing association. Of the 8 groups of properties in the monitoring programme:

- 231 are of the solid-walled, post-1919 houses and 4-in-a-block, (Shettleston, Mosspark);
- 179 are of the inter-war, non-cavity houses (Carntyne);
- 96 are a mix of 1920s non-cavity tenement flats and 1960s maisonettes flats (Shawlands);
- 116 are pre-1919 solid walled traditional stone tenements (Yoker); and
- 95 are 1950s/60s low and high-rise blocks (Pollokshields, Anniesland, Drumchapel).

Other construction types significant to Glasgow but not covered in these 8 groups, include:

- 1940s steel-clad houses;
- 1940s prefabricated timber housing with minimal insulation; and
- 1940s and 1950s solid-walled concrete slab types.

The Scottish House Condition Survey estimates that approximately 67,000 householders in Glasgow are presently in fuel poverty and it is likely that the recent increases in energy prices will have increased this further. This equates to approximately 24% of all Glasgow households.

Householders in fuel poverty are defined as those who spend more than 10% of their annual income on fuel costs (The Scottish Fuel Poverty Statement, Scottish Government). The Scottish Government has committed resources to tackle fuel poverty through various grants and other schemes, including the Home Energy Efficiency Programme for Scotland: Area Based Schemes (HEEPS:ABS). This commenced in 2013, with Glasgow receiving £8.4 million in funding in the first year. This funding enabled Glasgow City Council to work with social landlords and private contractors to develop insulation projects, which would benefit those living in the most fuel poor areas of Glasgow.

In order to determine the areas of the city to target in the present project, Glasgow City Council used the Scottish Index of Multiple Deprivation (SIMD) data (income domain) to identify areas of fuel poverty. This was then mapped against fuel poverty data in the Energy Saving Trust Home Analytics Model, giving rise to the outcome depicted in Figure 1.

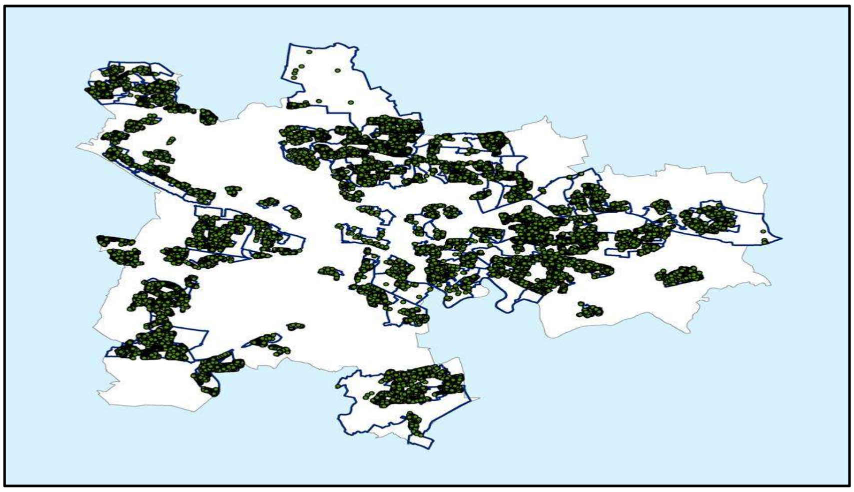


Figure 1: Fuel poverty distribution in Glasgow.

In addition to this, 65,000 properties in Glasgow have a poor-to-moderate National Home Energy Rating (NHER; SHSC, 2012). Installing or upgrading insulation is a most effective way to improve the energy efficiency of a building and the Energy Saving Trust estimates that an uninsulated dwelling loses a third of all heat through its walls. As a result, wall insulation can significantly increase thermal comfort and reduce heating bills.

The Energy Companies Obligation (ECO), which began in 2013, provides funding to insulate hard-to-treat cavity (HTTC) walls. Dwellings with HTTC walls are generally more expensive and complex to insulate than standard cavity walls. All properties in Glasgow City Council's HEEPS:ABS programme are ECO funded and therefore fall into the HTTC category.

It is for these reasons that the Glasgow Future Cities Demonstrator project reported here targeted specific areas for study: properties that fall under fuel poor areas of Glasgow, with HTTC walls and that are being part-funded through Glasgow City Council's HEEPS:ABS programme.

The majority of the work being carried out under HEEPS:ABS is external wall insulation (EWI) as this measure allows the biggest carbon savings per property, which is a key aim for the Scottish Government. As the study focussed on properties included in HEEPS:ABS, the majority of findings relate to EWI work but with some cases addressing internal wall and underfloor insulation.

The building type and age of the properties also were a factor in determining dwellings to target. According to the SHCS (2012), 26% of Glasgow's housing stock was built before 1919, 18% from 1919-1944, 23% from 1945-1964, 12% from 1965-1982, and 20% from 1982 onwards. While it was the intention of the study to address a sample of these properties, some constraints were encountered as work was not carried out on all property ages and types. Instead, the project attempted to obtain as representative a sample as possible.

3. Project monitoring programmes

The groups of properties monitored are listed in Table 1, with each group comprising houses with the same construction.

Table 1: Dwellings selected for monitoring.

Group	Build type	House form	Upgrade number	Insulation upgrade	Monitored houses
Shettleston 1	1950s steel frame, solid brick wall (Atholl)	Semi-detached terrace, 4-in-a-block	231	External wall	5
Shettleston 2	1920s cavity brick/concrete block	Semi-detached		Underfloor & glazing	3
Pollokshields (Sherbrooke Dr.)	1960s solid brick wall	Flat	47	External wall, roof	4
Carntyne 1	1920s concrete frame, clinker concrete cavity walls (Winget)	Semi-detached houses	134	External wall	3
Carntyne 2	1920s terrazzo block cavity wall	Semi-detached, 4-in-a-block	45	External wall	6
Mosspark	1920s solid concrete block	Semi-detached houses	No programme	External or internal wall	4
Drumchapel	1950s solid brick wall	Flat	24	External wall	6
Shawlands 1	1920s cavity concrete panel / brick	Tenement flat	48	External wall	2
Shawlands 2	1960s cavity concrete panel/ concrete	Maisonette two floors in multi-storey	48	External wall	6
Yoker	Sandstone solid wall	Tenement flat	116	External wall	6
Anniesland	Solid concrete/brick high rise	Flat	24	Internal wall	4

Not all properties were actually upgraded within the duration of the project, and some difficulties were experienced in recruiting occupiers in properties that were scheduled for upgrade – partly due to the majority of upgrade work taking place during summer months. A number of properties were therefore included that were not due for insulation upgrade (at least within the project timescale) or had already been upgraded. In many cases it was possible to select properties in the same group with and without the insulation upgrade. An adapted analysis technique was devised for these properties so that, in conjunction with building performance simulation, it was possible to draw conclusions about likely insulation performance.

Generally, 100 mm external wall insulation was applied and houses already had loft insulation. In Mosspark, internally and externally applied insulation approaches were compared. Figure 2 depicts typical examples of dwellings before and after insulation upgrade.

Figure 2: A typical uninsulated property in Carntyne (left) and an externally insulated property in Shettleston (right).

4. Selection of dwellings for assessment

Were the dwelling selection process to be based on random sampling of properties, a 1/9th replicate would be typically required to ensure that the variations in energy use due to occupancy pattern and indoor temperature preference were captured. Further, the real-time basis of the insulation upgrading programme meant that each upgrade begins almost immediately after the occupant has agreed to take part, so before-and-after monitoring was not always practicable: 2–6 properties in each of the 11 groups were monitored over an extensive period and, where possible, before-and-after and side-by-side comparisons of upgrades where undertaken. To reduce the required sample size, a modelling approach was employed whereby the monitored temperatures from a sample of properties were used to calibrate a detailed model of each house type. These models were then simulated to produce energy saving benchmark data in relation to the specific insulation deployments.

Ideally, the annual heating fuel consumption in each house should be known, and the two monitored houses selected randomly from the middle two quartiles as a means to select houses with typical heating energy consumption as opposed to outliers. However, due to data privacy the electricity or gas consumption could only be known after an occupant had agreed to take part in the programme. Because of this, the monitored houses were selected opportunistically, on the basis of which occupants were willing to participate at the time. This equates to a semi-random sampling method as there is unlikely to be a correlation between the willingness to participate and the energy use pattern.

Tables 2(a) and 2(b) detail the construction type for each of the properties monitored and also the placement of the sensors used to collect environmental data. The information shown is typical of that which is gathered on site for the subsequent selection and scaling of dynamic simulation models. Construction details were obtained from original plans extracted from the GCC archive (see Figure 11).

Table 2(a): Details of monitored dwellings.

Location (date installed)	ID	Sensor location 1	Sensor location 2	Floor area (m^2)	Building type	Insulation Loft (mm)	Insulation New	Occupancy
Shettleston (06/2014)	SH1	Living room	Kitchen	70	Semi 2f	150	Ext	1ar
	SH2	Back bedroom	Kitchen	80	4b Flat, TF	0	None	1ar
	SH3	Front room	Kitchen	92	Semi 2f	150	Ext	1ar
	SH4	Front bedroom	Kitchen	140	4b Flat, TF	0	None	2aw, 2c
	SH5	Back bedroom	Kitchen	84	Semi 2f	150	Ext	2aw, 1an
Mosspark (06/2014)	MO1	Living room	Kitchen	106	Semi 2f	150	Int	2aw, 2c
	MO2	Living room	Kitchen	106	Semi 2f	0	None	2aw, 1c
	MO3	Living room	Kitchen	140	Semi 2f	150	Ext	2aw
	MO4	Living room	Kitchen	120	Semi 2f	0	None	2ar
Sherbrooke (06/2014)	SB1	Bedroom	Kitchen	108	Mais TF 2f	0	Ext	2ar, 1aw
	SB2	Bedroom	Kitchen	80	Flat TF	0	Ext	1aw,1an,4c
	SB3	Spare room	Dining room	80	Flat MF	-	Ext	1aw
	SB4	Office	Kitchen	80	Flat TF	0	Ext	1aw
Carntyne (07/2014)	CA1	Bedroom	Kitchen	81	Flat GF,4b	-	Ext	1ar
	CA2	Living room	Kitchen	81	Flat GF,4b	-	None	1ar
	CA3	Living room	Kitchen	81	Flat TF, 4b	150	Ext	2aw, 1c
Drumchapel (11/2014)	DR1*	Living room	Kitchen	96	Flat MF	-	None	2ar
	DR2*	Living room	Kitchen	96	Flat TF	0	None	2aw
	DR3*	Living room	Kitchen	96	Flat MF	-	None	2aw
	DR4*	Living room	Kitchen	96	Flat GF	-	None	3aw
	DR5*	Living room	Kitchen	96	Flat GF	-	None	2ar
	DR6*	Living room	Kitchen	96	Flat GF	-	None	1ar
Shawlands (11/2014)	SL3*	Living room	Kitchen	90	Flat GF	-	None	1ar
	SL4*	Living room	Kitchen	90	Flat TF	0	None	4aw
Carntyne 2 (11/2014)	CA4*	Top bk bedroom	Kitchen	90	Semi	50	none	2ar
	CA5*	Top bk bedroom	Kitchen	90	Semi	50	none	2aw
	CA6*	Top bk bedroom	Kitchen	90	Semi	50	none	3aw, 1c
	CA7*	Back bedroom	Kitchen	70	4b GF	-	none	1ar
	CA8*	Back bedroom	Kitchen	90	Semi	50	none	1ar
	CA9*	Back bedroom	Kitchen	70	4b GF	-	none	1an
Shawlands 2 (01/2015)	SL5*	Back bedroom	Kitchen	100	Mais 2f TF	0	None	1an, 3c
	SL6*	Back bedroom	Kitchen	100	Mais 2f TF	0	None	1aw
	SL7*	Back bedroom	Kitchen	100	Mais 2f MF	-	None	1ar
	SL8*	Back bedroom	Kitchen	100	Mais 2f TF	0	None	1aw
	SL9*	Front bedroom	Kitchen	80	Mais 2f MF	-	None	2ar
	SL10*	Front bedroom	Kitchen	80	Mais 2f TF	0	None	2ar
Yoker (02/2015)	Y1	Kitchen	Living room	72	Flat MF	150	Ext	2aw
	Y2	Kitchen	Living room	72	Flat GF	150	Ext	2anw
	Y3	Kitchen	Living room	72	Flat MF	150	None	1an, 2c
	Y4	Kitchen	Living room	72	Flat MF	150	Ext	2ar
	Y5	Kitchen	Living room	64	Flat MF	150	None	1ar, 2aw
	Y6	Kitchen	Living room	72	Flat MF	150	None	1an
Shettleston 2 (02/2015)	SH6*	Kitchen	Front Bedrm	76	Semi 2f	150	uf/dg	1ar
	SH7*	Kitchen	Bedroom	76	Semi	150	uf/dg	2ar
	SH8*	Kitchen	Front Bedrm	76	Semi 2f	150	uf/dg	1aw,1an,1c
Anniesland (03/2015)	AN1*	Kitchen	Living room	73	Flat MF	-	Int	1ar
	AN2*	Kitchen	Living room	73	Flat MF	-	Int	1aw,1an,2c
	AN3*	Kitchen	Living room	73	Flat MF	-	Int	1an
	AN4*	Kitchen	Living room	49	Flat MF	-	Int	1an

Table 2(b): Construction of monitored dwellings.

Location	Construction	Glazing	Age
Shettleston	Render–brick–gq–pbd	Double	1950
Mosspark	Stone–ag–brick–plaster	Double	1920
Sherbrooke	Render–brick–ag–pbd	Double	1962
Carntyne	Render–cpanel–ag–pbd	Double	1920
Drumchapel	Render–brick–ag–pbd	Double	1950
Shawlands	Concrete–ag–brick–pbd	Double	1920
Carntyne 2	Terrazzo blocks–ag–timber–pbd	Double	1920
Shawlands 2	Concrete–ag–cpanel–pbd	Double	1964–1965
Yoker	Sandstone–ag–brick–plaster	Double	1885–1912
Shettleston 2	Roughcast–brick–ag–cblock–plaster	Single	1953
Anniesland	Mosaic–cpanel–woodwool–plaster	Double	1966

Key to abbreviations				Occupancy key	
2f	Two floors	Int	Internal	#an	No. adults not working
4b	four-in-a-block	Mais	Maisonette (two floors of multistorey)	#ar	No. adults retired
ag	airgap	MF	Mid floor	#aw	No. adults working
cpanel	concrete panel	pbd	plasterboard (gyproc)	#c	No. children
dg	double glazed	Semi	Semi-detached		
Ext	External	TF	Top floor		
GF	Ground floor	T&H	temperature and humidity		
gq	glass quilt	R/cast	Roughcast		
uf	underfloor	Int	Internal		

Properties selected for monitoring were either un-insulated, or already had external wall insulation applied. Typical external insulation thickness is 100mm. One exception is an owner/occupied property with partial internal insulation (property MO1).

5. Monitoring outcomes

Because the upgrades involved real world complexities stemming from occupant behaviour, changing weather conditions, construction scheduling, privacy impacts and the like, it was necessary to adopt an approach that could normalise for such factors. The following approach was elaborated and trialled within the project.

A weather station was installed at each site, except where two sites are sufficiently close together that one weather station can serve both sites. Each weather station transmits air temperature and humidity, and is located in a secure location, sheltered from solar radiation. This is typically in the garden area of one of the monitored dwellings. Other weather data required for computer simulation (e.g. solar radiation and wind speed) is obtained from the nearest meteorological station.

The equipment required to monitor indoor conditions comprises two combined temperature and humidity sensors located within each dwelling, each with a built-in low power radio transmitter. A single radio receiver associated with each group of dwellings collects data from each sensor at 5-minute frequency. The receiver records the readings and these are then downloaded periodically. Sensors within properties have to be positioned in such a manner as to obtain a reasonable measure of temperature and humidity, but at the same time be unobtrusive to occupants and not susceptible to interference. For properties located far from the receiver, it is necessary to install longer antennae, and to position sensors at elevated positions within rooms. To provide consistent measurements of room conditions, it is also necessary to ensure that each sensor is not moved significantly away from its location during the monitoring period, particularly if a property is insulated during that period. Small adjustments may be made to sensor readings to simulate a centre-of-room positioning. In each dwelling, one sensor is installed in a living or bedroom area, and a second sensor is installed in a kitchen or bathroom depending on where high humidity levels are likely to be experienced.

Figure 3 shows the sensor/transmitter and receiver equipment deployed, while Figure 4 depicts a typical installation – the sensors are highlighted with red arrows; as can be seen, the visual impact for the occupant is minimal. This scheme generates the information required to subsequently calibrate the dwelling models, and requires minimum interaction with the resident.

Figure 5 depicts typical temperature recordings from two of the Shettleston group of houses over a 3 day period. The most dominant variation that can be observed follows the diurnal fluctuations in outside temperature (the lower curve). Despite these being similar properties, there is a wide variation in temperatures due to occupant behaviour. One property (SH4) exhibits a distinctly higher temperature than the others, with occasional daily peaks in the kitchen, most likely due to cooking activity. Other occupant and heating system behaviours may be deduced by inspection of the graphs – some examples are shown in the figure. (See Appendix B for a summary of project outcomes per dwelling.)

Figure 3: BuildAX receiver/sensor (left) and Eltek receiver/sensor (right).

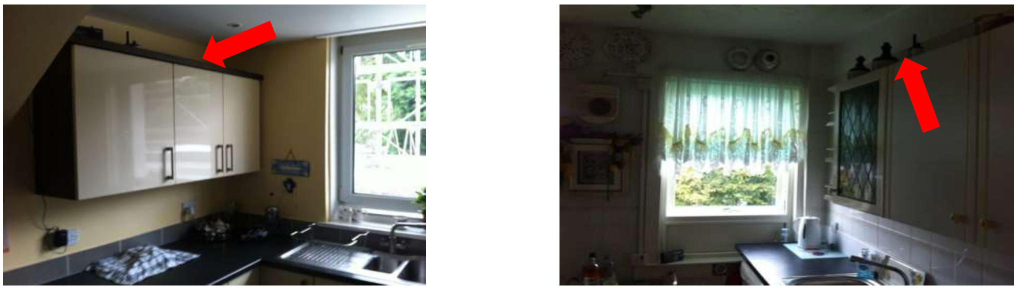


Figure 4: A typical monitoring installation.

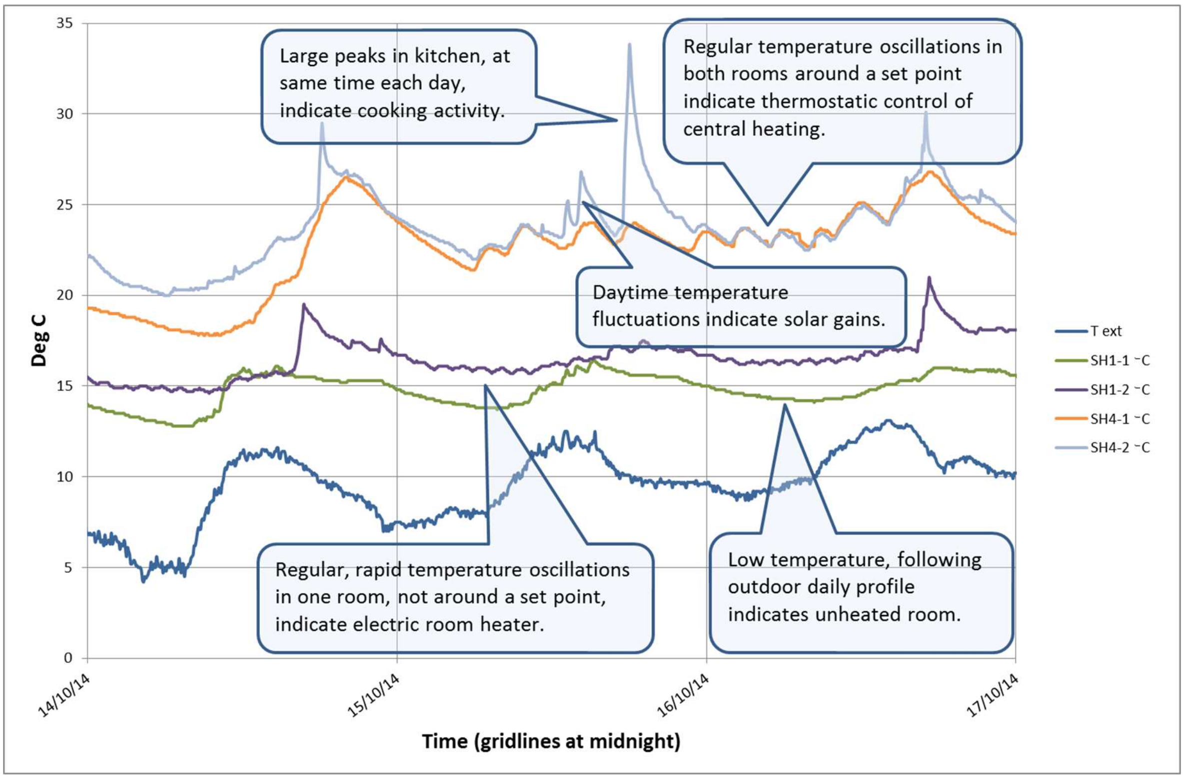


Figure 5: Typical temperatures (C) in two of the Shettleston properties.

Figure 6 shows typical variations in relative humidity in the same group of houses (the upper curve is the outside air humidity). Occupant and heating system behaviours may be deduced by inspection of the graphs – some examples are shown in the figure. Note that internal humidity levels are strongly related to internal temperature. A rise in temperature will lead to a fall in RH, without any moisture addition or removal. Considerable variation exists between properties, although most fall in the acceptable range of 40-60% RH. One exception (SH1) exhibits variations up to 80% RH. It is known that the resident is disabled, and this might have a bearing on the data pertaining to this property. This property has been insulated, so an investigation might be called for here to ensure no internal condensation problems are occurring, particularly at thermal bridges.

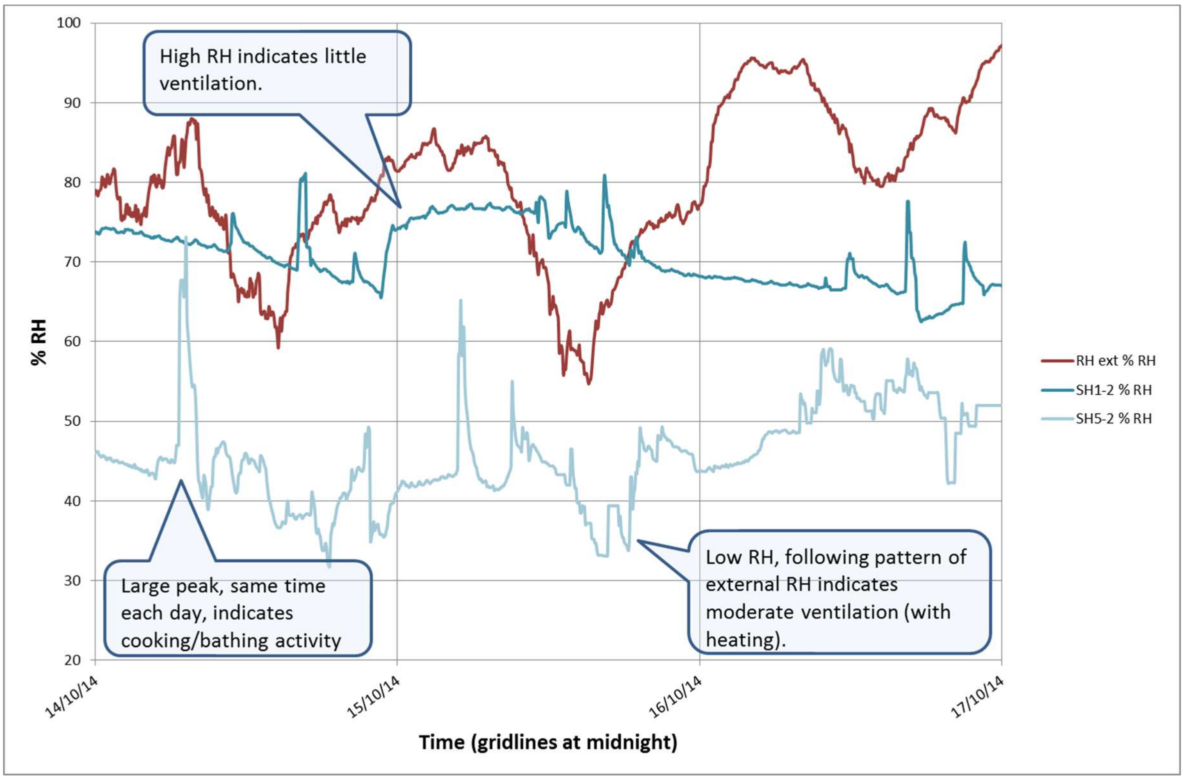


Figure 6: Typical relative humidity (%) in two of the Shettleston properties.

One property (SB2) exhibits severe mould growth problems on the inside surface of the outer walls (Figure 7).

Figure 7: Occurrence of a severe mould growth problem.

Closer inspection revealed that mould has formed on the double glazed window seal, suggesting that condensation has been forming on the inner pane of the window. This suggests that the problem is condensation, not a building fault. The property is occupied by a family with four children, a higher occupancy level than other properties in the group. The recorded data shows particularly high humidity levels regularly exceeding 80% RH. While the insulation applied to this property reduced the condensation problem on the walls, further inspection would be required to detect if any residual cold bridges have been created during the insulation process as this could become a problematic source of hidden dampness. In any case, this is a site where advice should be given to the occupant concerning the need for additional ventilation (window opening) when cooking, bathing and indoor clothes drying.

An example of a cold bridge is shown in Figure 8, where insulation has been omitted around a gas meter and pipework.

Figure 8: thermal bridge due to non-insulated section around a gas pipe and meter box.

Consideration should be given to careful internal inspection after a period of time to identify the incidence of dampness problems cause by such omissions and remedial action should be taken where necessary. Examples include the exceptional observations of Table 3 (note that individual dwellings may fit into more than one category).

Table 3: Environmental data.

Cat.	Temperature	Humidity	Energy use*	Potential diagnosis
1.	High for extended periods	Any	High	Poor temperature control / wasted energy.
2.	Low for extended periods	Any	Low	Fuel poverty alert.
3.	High peaks	High peaks	Any	Poor ventilation during cooking / bathing
4.	Medium	High for extended periods	Any	Poor ventilation at all times / internal clothes drying.
5.	Low	High	Any	As 3. with high internal condensation risk
6.	Wide range	Low / medium	High	Excessive ventilation (maybe window opening).
7.	Low / medium	Any	High	Check for thermal bridges.

* In this table, energy relates to usage relative to norms established through modelling.

The above diagnoses will be tempered by correlating the observations with maximum occupancy levels, and average outside temperature and humidity conditions. For example, a high internal humidity level in winter when external humidity is high is of lesser concern than when external humidity is low. High internal humidity peaks are of less concern if occupancy is high. A priority rating system is proposed that, as a demonstration of a potential energy-related service, could be generated through automated data analysis via an intelligent agent.

6. The POET tool for quality assurance of upgrades

A Post Operations Evaluation Tool (POET) was developed to provide a method for the automatic confirmation of the quality of an insulation upgrade. POET implements a procedure to assess the energy and environmental efficacy of the upgrade. This provides an evidence-based quality assurance test of the upgrade that supports project sign-off.

An image of the POET user interface is given in Figure 9. The tool requires basic information on the property such as its archetype, construction, occupancy, floor area, upgrade type, and a suitable weather station location to be used in the analysis. (Although not shown here, the user may enter additional details about the property that, while not required by the energy and environmental assessment algorithms, may be used to populate project sign-off reports.)

The tool utilises meter readings and monitored indoor conditions data in order to assess the insulation upgrade. As shown in Figure 9, the user can select from three types of electricity meter (standard, dual, white) or two types of gas meter (m^3, ft^3).

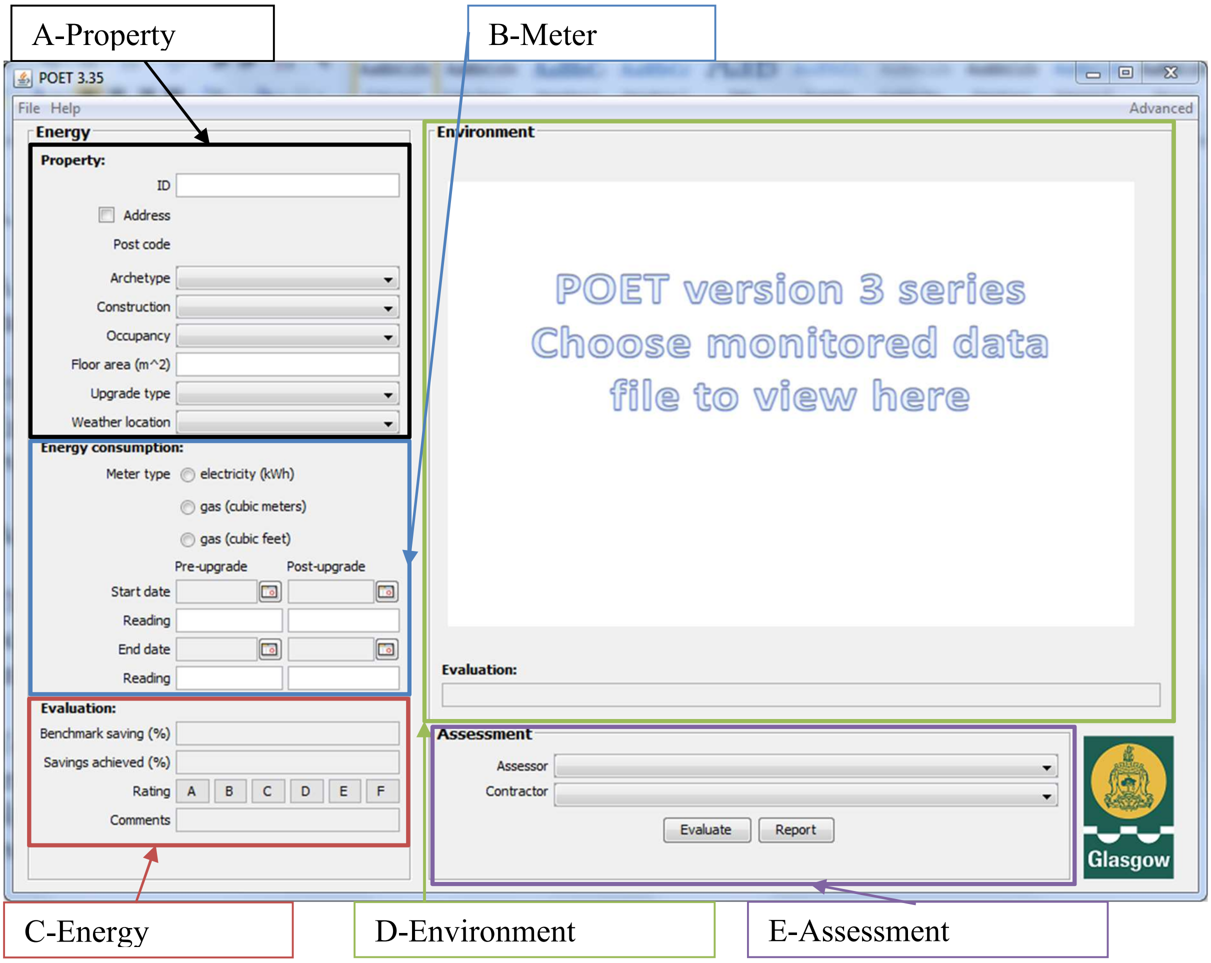


Figure 9: Constructs within the POET interface.

Feedback is provided based on analyses relating to energy performance and post-upgrade internal environmental conditions.

Based upon the property details entered in section A, a predicted energy performance benchmark is selected from a database of ideal performance benchmarks as determined from dynamic computer simulation (see §7). This is then displayed in the 'Benchmark saving (%)' field. The pre- and post-upgrade energy consumption of the dwelling, determined from meter readings entered in section B, is normalised using the relevant outdoor temperature data from the selected weather station. This determines the savings achieved by the property's upgrade and is displayed in the 'Savings achieved (%)' field (section C). The benchmark saving is compared to the actual saving achieved and a bar is displayed showing how close the property came to achieving its theoretical value. This information used alongside the property energy survey data allows an assessor to determine if the upgrade has achieved its expected goal.

Once the monitored environmental conditions have been imported, a preview image is generated in section D as depicted in Figure 10 along with indicators marking the pre- and post-upgrade meter reading periods. Clicking on the image displays an interactive graph allowing the user to switch on and off specific data profiles or zoom in to examine the monitored data over different time periods.

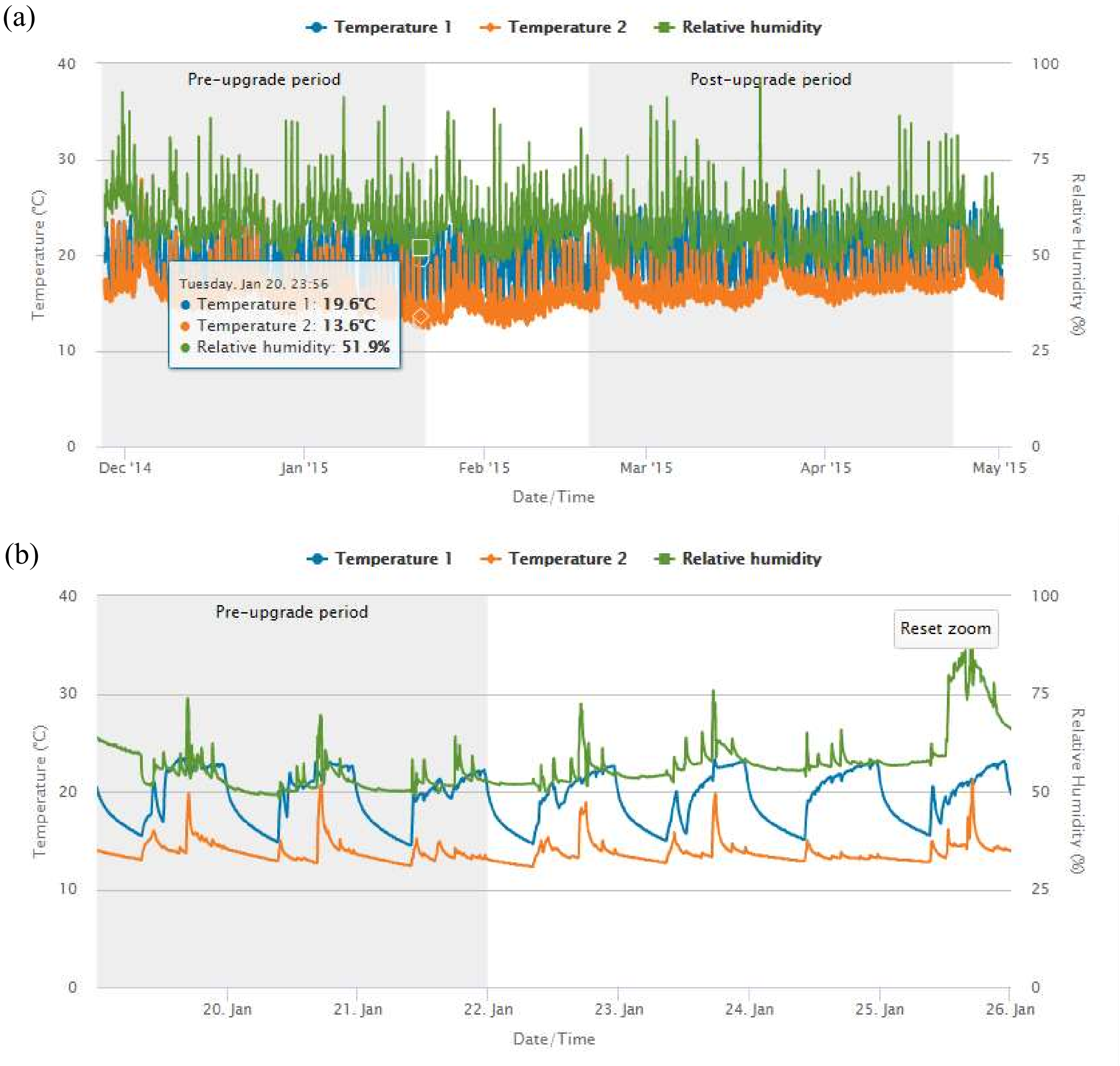


Figure 10: Interactive POET graph – (a) all monitored data, (b) a one week period.

A field is provided under the preview image that gives textual feedback from an underlying environmental conditions assessment algorithm. This algorithm assesses the post-upgrade indoor temperature and humidity profiles as monitored in order to determine if these are within acceptable ranges. The tool also provides an interface for changing the acceptable performance ranges.

This interactive viewing facility, when used in conjunction with the written feedback from the environmental assessment algorithm and the survey information, provides the assessor with an analysis tool for identifying acceptable indoor environmental performance post-upgrade and isolating possible causal factors where this performance is deemed unacceptable. Details on the energy and environmental assessment algorithms are available from within the POET interface.

The assessment section of the tool (section E) allows the user to input information regarding the assessor selected from a database of previous assessors. Additional assessors and contractors can be added by authorised users via the advanced menu. This section of the tool launches the evaluation of the algorithms, and generates a compliance report. The report was specified by GCC and provides a summary of the dwelling's performance along with any recommendations for follow-up action.

In order to test the operation and application of the tool, it was deployed within the GCC's Housing Strategy Group and subjected to user trial using sample data as collected within the project and representing different possible upgrade outcomes (acceptable, unacceptable and ambiguous). Tool functionality was evolved in response to user feedback.

7. Energy saving benchmarks

A detailed computer model was constructed for each monitored dwelling as listed in Table 2. These models were constructed on the basis of architectural drawings provided by GCC and information gathered during site visits. The models, after calibration against monitored data, were subjected to computer simulations over the heating season to determine the theoretical heating energy saving potential associated with each of the proposed insulation upgrade schemes. This theoretical value may then be compared to metered outcomes. A supplementary capability of these models is to support investigations into the causes of post-insulation problems as observed in the field.

What follows is an exemplar of the modelling procedure. The specific example corresponds to a dwelling in Shettleston, with the calibration process based on monitored data as collected during the project. The data required for model creation is as follows.

1. The three-dimensional geometry of the dwelling, for creating model zones and defining the dwelling envelope.
2. A database of constructions for the dwelling fabric and glazing.
3. Parameters of the heating system and its control settings.
4. The occupancy profile for the dwelling, including estimates of activity.

Steps one and two begin via inspection of architectural drawings, an example of which is given in Figure 11. Additional information was extracted from prior versions of the Building Regulations relevant to the year of construction. Due to the age of the properties, and of the architectural drawings themselves, complications naturally arose in determining and interpreting the exact specifications of the building geometry and its construction. Where insufficient information was available directly from the drawings or relevant regulations, site visits were used to acquire missing information, and also to validate the data provided in the drawings. This quality-assurance step is necessary to ensure that the benchmark performance determined for the property type is an accurate reflection of the theoretical limit of performance, and also to reduce the complexity of the calibration exercise.

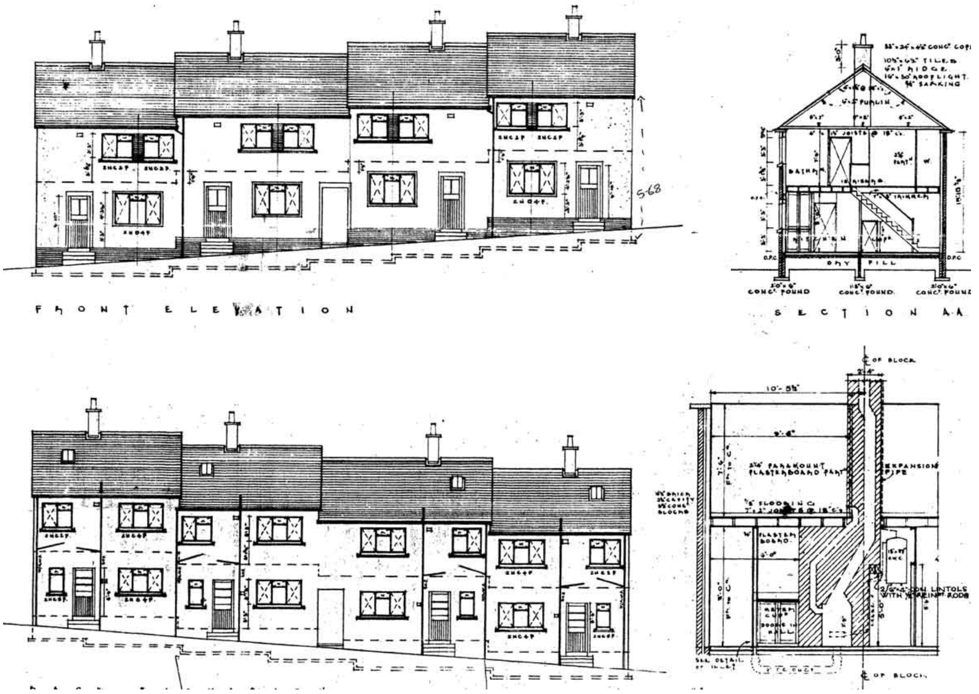


Figure 11: An architectural drawing as supplied by Glasgow City Council.

Determination of the heating system parameters was done via site visits. Most dwellings in the monitored group utilise a gas boiler with appropriately sized radiators in each room. Knowledge of the position of the thermostat in the dwelling was important as this will have an effect on the model calibration procedure.

The occupancy profile and related activity of the occupants is difficult to ascertain. The occupancy of the dwellings can vary considerably, from single retired adults who are generally at home, to families with two working adults and four children. Two occupancy profiles were created for use in generating the energy benchmark database: 1) continuous (16 hours – all day) and 2) intermittent (2 heating periods – 7 hours). It is anticipated that an assessor will use their expertise and the information gathered during the site survey to determine the most appropriate occupancy profile for selecting a benchmark from the database.

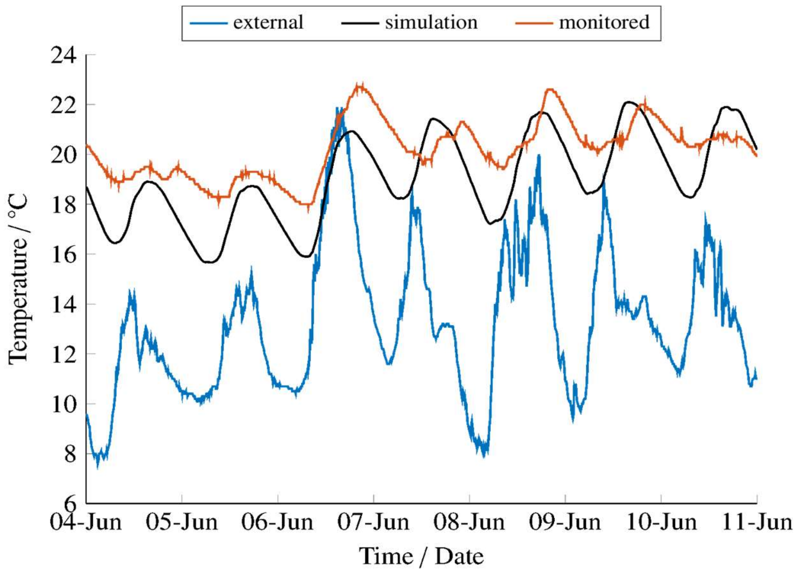
Calibration was carried out by comparing simulation outcomes with measured data. An example of the calibration procedure is provided here for a dwelling in Shettleston of Atholl type construction (steel frame, solid masonry) dating from 1951, arranged in a two-storey, semi-detached style cottage home. A description of the model is provided in Appendix A.

A representative week from each of the non-heating and heating seasons was chosen in order to represent the use-cycle of the building at distinct times of year. The calibration process consists of initially adjusting temperature set-points to match the actual thermostat settings. The sensor characteristics and internal thermal mass may then be adjusted to obtain a qualitatively similar response to dynamic inputs (external temperature, solar, heating switching, occupant activity *etc*.). Where required, the magnitude of temperature swings may be moderated by judicious adjustment to window coverings and infiltration rates.

Figure 12(a) shows an initial comparison between prediction and observation in a bedroom, while Figure 12(b) shows the improved match after completion of the model calibration process.

The calibration procedure utilises several criteria, including the mean temperature agreement, temperature swing (standard deviation from mean) and the root-mean-square-error, which is a measure of the variation in the residuals.

(a)



(b)

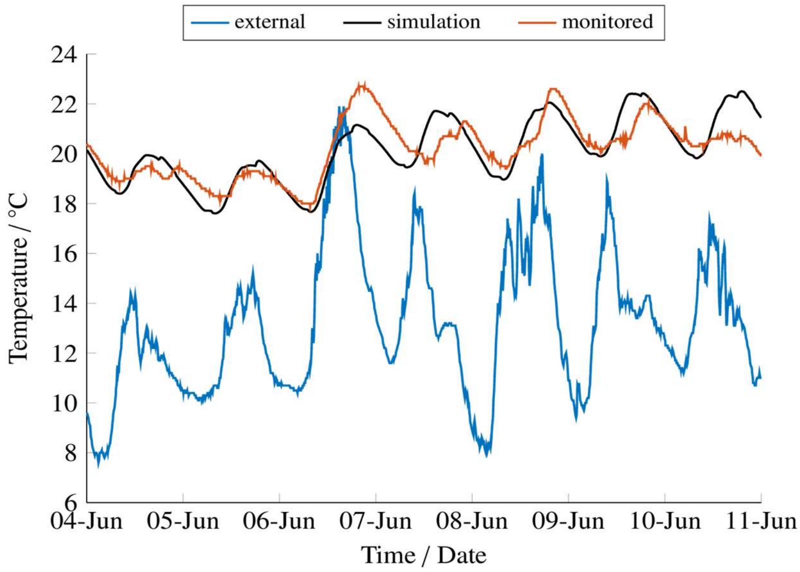


Figure 12: Comparison of predicted and measured temperatures;
(a) pre-calibration. (b) post-calibration.

In the present case, the following observations led to model adjustments to achieve the calibrated model.

- General under-prediction of room temperature – action: decreased infiltration rate of the dwelling and adjust the casual gains corresponding to a single occupant at home for the majority of the day.
- Gradient of temperature decay (heat loss) in evenings too steep – action: decreased *U*-value of property by adjusting thermo-physical properties of external construction.
- Amplitude (swing) of internal temperature from mean too high – action: increase internal mass (associated with furniture) of the property.

As can be seen from Figure 12(b), the calibrated indoor temperature of the bedroom shows good agreement with the sensed temperatures. Table 4 summaries the pre- and post-calibration modelling benchmarks for this example dwelling.

Table 4: Pre- and post-calibration model benchmarks

Criteria	Measured / °C	Calibration	
		Pre / °C	Post / °C
$\bar{\Theta}(\sigma)$	20.2(1.15)	19.0(1.77)	20.2(1.32)
RMSE	—	1.61	0.813

There are, however, a few points that should be noted in relation to the post-calibration results. On 7 June, the temperature is slightly under-predicted in the evenings, which is likely caused by a change in occupant behaviour on this day, such as the arrival of visitors. In addition, the temperature for 10 June is over-predicted, but is in line with the previous two days. This indicates that the property was possibly unoccupied during these days. Such specifics are not included in the model as the intent is to keep the operational details of the homes as general as possible. Also, the benchmark saving corresponds to the theoretical percentage reduction in post-insulation energy use with no behavioural change from the tenants, e.g. the heating thermostat is left unchanged and a fault-free insulation upgrade is assumed.

As the study focussed on properties included in HEEPS:ABS, energy performance benchmarks were predominately created for the external wall insulation case, while some additional benchmarks are provided for specific cases where internal wall or underfloor insulation was applied. Table 5 lists the benchmark savings to result for each monitored dwelling and as installed within the POET tool to support the automated quality assurance procedure.

Table 5: Energy performance benchmarks for monitored properties.

Location	Dwelling	Benchmark saving (%)
Shettleston	SH1	24.7
	SH2	18.6
	SH3	24.7
	SH4	13.1
	SH5	24.7
	SH6#	14.8
	SH7#	14.8
	SH8#	14.8
Mosspark	MO1*	16.4
	MO2	16.4
	MO3	12.9
	MO4	12.9
Sherbrooke	SB1	17.4
	SB2	21.6
	SB3	20.3
	SB4	22.9
Carntyne	CA1	18.2
	CA2	18.2
	CA3	11.4
	CA4	23.2
	CA5	15.6
	CA6	15.6

	CA7	24.1
	CA8	23.2
	CA9	24.1
Drumchapel	DR1	13.9
	DR2	22.9
	DR3	22.9
	DR4	21.9
	DR5	16.4
	DR6	21.9
Shawlands	SL3	24.6
	SL4	15.9
	SL5	22.9
	SL6	10.7
	SL7	14.2
	SL8	10.7
	SL9	14.2
	SL10	22.9
Yoker	Y1	16.4
	Y2	22.1
	Y3	20.3
	Y4	20.3
	Y5	20.3
	Y6	20.3
Anniesland	AN1*	13.5
	AN2*	13.5
	AN3*	13.5
	AN4*	13.5

All dwelling have EWI except where marked (#underfloor insulation, *internal wall insulation).

8. Project outcomes

Annual energy savings are calculated based on house type, construction, floor area and occupancy. This benchmark saving is then compared with actual energy consumption after adjustment has been made to allow for differing outdoor temperatures during the pre- and post-upgrade monitoring periods. This gives a quantitative measure of the effectiveness of the insulation upgrade. The actual energy consumption is also compared with the national average. Consumption higher than the benchmark or national average may reflect the occupants' desire for a high level of comfort or inappropriate heating system usage, but does not necessarily reflect on the quality of insulation upgrading. Inspection of the recorded temperatures may be helpful if further diagnosis is required.

Individual performance review feedback reports have been prepared for each of the properties as included in Appendix B (available separately). The format of these reports is as follows.

On energy

- The actual energy saving after insulation is compared to the associated benchmark figure and the upgrade impact rated.
- The energy consumption measured during the monitored period is used to estimate the annual energy consumption after weather normalisation, and this is compared with the Scottish average.

- In cases where no upgrade took place during the monitoring period, the benchmark energy saving relating to the house type, floor area and occupancy generates an estimate of the heating energy that would be (or has been) achieved by the upgrade.

On indoor environmental conditions

- A graph showing the temperature in monitored rooms along with the external temperature over a typical portion of the monitored period.
- For each room, an indication of the range of temperatures as measured is provided. This may be compared with an 'acceptable range' corresponding to that which an average occupant would report as being comfortable; here the range is 19C to 23C. Temperatures below 17C or above 25C are considered unacceptably low or high respectively. Attention is also drawn to any notable fluctuations outwith these limits and their duration. Generally, short duration fluctuations do not cause problems while longer duration fluctuations will need to be investigated.
- Graph showing the relative humidity in one room (usually the kitchen) are shown along with the corresponding external values over a typical portion of the monitored period.
- Again, the range of values of relative humidity is given alongside an indication of the acceptable range: 40% to 70% with lower or higher values deemed unacceptable. Generally, short duration fluctuations do not cause problems while longer duration fluctuations will need to be investigated.

Summary

- This section summarises the main findings relating to the energy and environmental performance of the dwelling after upgrade.

Recommendations

- This section of the dwelling report gives recommendations where significant risk factors relating to health and/or fabric protection are detected, or the expected energy saving is not being realised.

It is also possible to draw general conclusions relating to the 'pervasive sensor' approach to the evidence-based quality assurance of upgrades as follows.

On sensor deployment

- Initial deployment at least one week prior to upgrade works commencing.
- Position away from windows and doors and out of reach of children.
- Advise occupant not to move sensors except for cleaning.
- Advise occupant not to disconnect logger from mains.
- Estimate total floor area, note building archetype (see Table 2) and construction type (or obtain from housing association).
- Remove sensors after second post-upgrade meter reading.

On meter readings

- Prior to sensor deployment, check fuel type and metering arrangements. Obtain guidance from utility supplier as appropriate, particularly in case of multiple meter displays.
- Pre-upgrade – one reading on sensor deployment and one on commencement of upgrade.
- Post-upgrade – one reading on completion of upgrade works and one at least one week later.

In the case of insulation upgrades undertaken in the summertime, it will be necessary to arrange for the pre- and post-upgrade monitoring to take place during consecutive heating seasons. Where this is not possible, post-upgrade monitoring will still provide a valuable indication as to the internal environmental conditions after insulation deployment, and highlight any concerns where temperature and relative humidity measurements are exceeding recommended limits. Other factors that may affect the post-upgrade energy saving calculation include:

- occupants taking a holiday so that the property is unoccupied for several days; and
- periods of high outdoor temperature (normally during the Spring/Autumn) causing the heating system to switch off and internal temperatures to rise above normal controlled levels.

The procedures described above can readily be applied to non-domestic buildings. To demonstrate the potential, sensors were deployed in a portion of Glasgow City Council's office where occupants were complaining about unacceptable environmental conditions – temperature, relative humidity and light levels were included in the data collection. Figure 13 shows the temperatures recorded over a one day period in July.

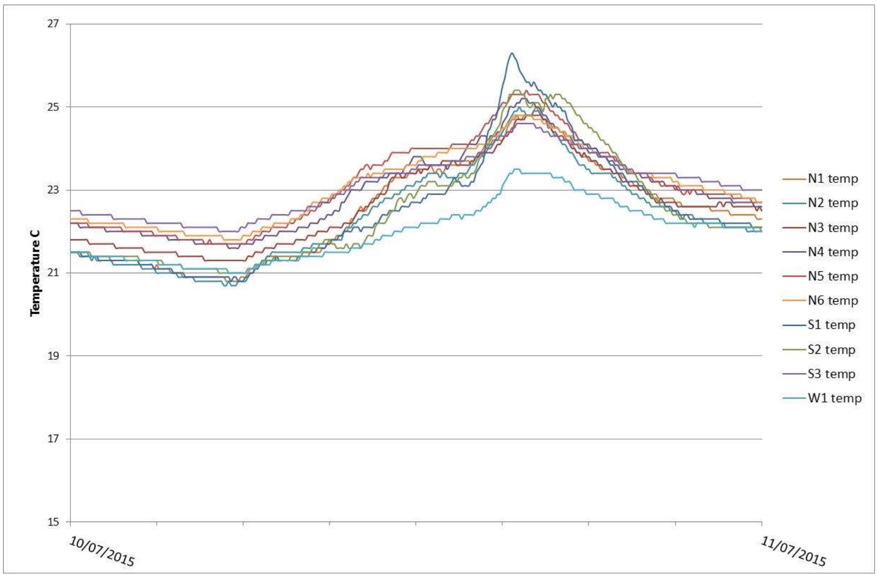


Figure 13: Temperatures from 10 sensors in an office over a one day period.

The readings were within ±1C of each other, except mid-afternoon when solar radiation caused disparate peaks to occur. These observations show that there is poor temperature control within the space, with temperature rising by ~5C over the working day. The ability to rapidly deploy sensors in this way to quantify such problems should assist facility managers to take evidence-based steps to ameliorate environmental problems in their areas of responsibility.

References

The Scottish Fuel Poverty Statement, Scottish Government, http://www.scotland.gov.uk/Publications/2002/08/15258/9955.

Scottish House Conditions Survey 2012, Scottish Government, http://www.scotland.gov.uk/Publications/2013/12/3017/290984#f15.

National Home Energy Rating information, http://www.nesltd.co.uk.

Appendix A
Example model description

An example of the computer modelling procedure adopted within the project is provided in this section. The example model is located in Shettleston, is of Atholl type construction dating from 1951 (steel frame, solid masonry), arranged in a two-storey, semi-detached style cottage home. The home was zoned based on estimated activity, such that the three bedrooms on the top floor can be modelled as a single zone, but separate zones are created for the hall, living room, kitchen and bathroom to respect user behaviour.

Table A1 summarises the model zoning procedure for the dwelling and highlights the typical information required.

Table A1: Exemplar dwelling zone geometry.

Zone	Area (m^2)	Envelope	Area (m^2)	Boundary Condition	Contruction	Windows /Doors	Area (m^2)
Ground floor							
hall	10.4	front_wall	3.912	exterior	atholl_steel		
		part_hall_lr	8.409	another	part_1951	hall_lr_dr	1.51
		part_hall_kn	2.642	another	part_1951		
		part_hall_bt	4.114	another	part_1951	hall_bath_dr	1.51
		ext_wall	11.783	exterior	atholl_steel	hall_win_glz	0.622
		hall_ceiling	10.449	another	first_floor		
		hall_floor	10.449	ground	gnrd_floors		
living_room	18.6	front_wall2	9.345	exterior	atholl_steel	lr_win_glz	2.672
		simr_wall	9.919	similar	party_walls		
		part_lr_kt	11.176	another	part_1951	lr_kt_dr	1.51
		lr_ceiling	18.613	another	first_floor		
		lr_floor	18.613	ground	gnrd_floors		
bathroom	4.37	part_bt_kt1	0.53	another	part_1951		
		part_bt_kt2	4.802	another	part_1951		
		ext_bt_wall	4.919	exterior	atholl_steel	bt_win_glz	0.988
		ext_br_wall2	4.802	exterior	atholl_steel		
		bt_ceiling	4.372	another	first_floor		
		bt_floor	4.372	ground	gnrd_floors		
kitchen	13.6	sim_kt	7.444	similar	party_walls		
		ext_wall_kt	9.159	exterior	atholl_steel	kt_win_glz	0.988
						back_door	1.761
		kt_ceiling	13.592	another	first_floor		
		kt_floor	13.592	ground	gnrd_floors		
First floor							
bedrooms	47	frt_wl_uppr	14.37	exterior	atholl_steel	fnt_glz	3.15
		sim_wl_uppr	17.363	similar	party_walls		
		back_wl_uppr	14.984	exterior	atholl_steel	bck_glz	2.66
		ext_wl_uppr	17.363	exterior	atholl_steel		
		uppr_ceiling	47.026	another	first_floor		
Upper floor							
roof_space	--	left_roof	7.857	exterior	atholl_steel		
		fnt_roof	28.765	exterior	roof_2		

right_roof	7.857	similar	party_walls
bck_roof	28.765	exterior	roof_2

Once the model has been zoned, the next step in the procedure is to assign constructions to the envelope elements.

The dwelling has a traditional domestic control system that utilises a gas boiler and appropriately sized radiators in the hall, living room, bathroom and bedrooms. A wall-mounted thermostat was placed in the hall, with the heating system acting to maintain an indoor temperature of 21C. It is assumed that occupants utilise the summer and winter settings of the boiler such that the system is disabled in the summer and active in the winter.

The model thermostat is configured to measure an appropriate mix of room air and wall surface temperatures. Experience suggests that the typical ratio of air to mean surface temperatures for the sensors deployed is 1:2 and this may also be further affected by less than ideal sensor positioning. Each sensor data logger is deployed sympathetically to the occupant wishes, which often results in the equipment being placed in a confined location adjacent to a wall, as is the case for this dwelling. The consequence of this is that the sensor model must also be considered as part of the model calibration process.

Appendix B
Dwelling performance outcomes by upgrade area and dwelling

This appendix is available as a separate document.