Building Performance Evaluation – A design approach for refurbishment of a small traditional building in Scotland

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Abstract - *In recent years, thermal performance improvements have been applied to an increasing number of historic buildings towards the achievement of the legally binding Scottish carbon dioxide (CO_2) emission reductions. Over 20% of the built environment in Scotland was constructed pre 1919 and the targeting of fabric improvements in these buildings can pose a performance risk if inappropriate measures are applied. This paper discusses through a case study a Building Performance Evaluation (BPE) approach used in conjunction with the design process for refurbishment of a community owned historic building, located in Arisaig, Scotland. The community received funding to improve the energy performance of this 19th century stone building and committed to a 75% reduction in CO_2 emissions. BPE was conducted in 2014 as part of the design process and repeated post-refurbishment in 2015 to validate the design. The initial BPE identified high heat losses, inefficient heating and lighting systems that resulted in occupant discomfort, high running costs and consequently the loss of a community facility during the winter months. The resulting BPE quantified improvements to the building fabric, occupant comfort and reduced energy consumption, which advocated this design approach as a beneficial tool for informing historic building refurbishment.*

Keywords - Refurbishment; Building Performance Evaluation; Energy; Sustainability; Indoor Air Quality

1. INTRODUCTION

Scotlands' ambition towards a low-carbon economy [1] and the promotion of energy efficiency schemes has in recent years led to an increased adoption of thermal improvements to historic buildings throughout Scotland [2]-[3]. This is particularly important as historic and traditional buildings play a major role in the fabric of our urban and rural spaces, refurbishing them in ways sympathetic to their character and fabric will ensure their longevity for future generations [4]-[6]. Scotland's built heritage plays a particular role in remote highland and island communities and contribute to a sense of place.

Over 400,000 (more than 20%) of Scottish buildings pre-date 1919 and offer considerable potential for carbon dioxide emission reductions [4]-[5]. This issue is increasingly important since the recent introduction for the assessment of energy performance of Non-Domestic Buildings (Scotland) Regulations 2016, requires all existing non-domestic buildings over 1000m^2 to undergo energy performance upgrades and hence carbon dioxide reductions within 3.5 years of being sold or leased to new tenants [8]-[9]. This aligns with the revised section 63 of the Climate Change (Scotland) Act 2009, and contributes towards the Scottish Governments ambition for a low-carbon economy. As well as improving the sustainability of buildings, energy efficient refurbishment also has the potential to improve the thermal comfort and health and wellbeing of occupants [4]-[6],[10]-[11].

While the reduction of carbon dioxide emissions through improved energy performance plays an important role in reducing the impact of climate change, the solutions and materials used to achieve these measures should improve the thermal performance of a building without compromising the character and fabric of traditional buildings [12]. It is particularly important to consider the impact on the existing ventilation and moisture performance of the building [4]-[6]. Building pathology analysis identifies incidences of sick building syndrome relating to the inappropriate use of materials which can cause adverse effects on occupants due to increased moisture, high volatile organic compound (VOC) and formaldehyde concentrations [10]-[11].

Research specific to the Scottish climate undertaken by Historic Environment Scotland has provided an evidence base for materials and appropriate construction methods as a baseline of information for refurbishment approaches [5]. Since original construction details of these highly individual buildings are rarely available to inform designers for development of robust refurbishment strategies, there is a risk that a one-size fits all approach to thermal improvements can have unknown outcomes. In addition, as the building fabric degrades over time this can lead to moisture ingress, condensation and dampness, all of which can lead to mould growth, degradation of the building fabric and could cause illness in occupants [11]. Therefore maintenance programmes for historic buildings often do not aim to improve the energy performance but unintended outcomes can arise from these interventions. This can occur for domestic and non-domestic buildings. Therefore, there is a pressing need for more evidence based case studies as there is much that can still be learned and understood for safeguarding the historic built environment, this can be partly achieved through building performance evaluation (BPE) and monitoring of buildings pre and post refurbishment.

This paper introduces a case study building, the Land Sea and Islands Centre (LSIC) located in Arisaig, Highland Scotland, where BPE was undertaken to provide information on the current building condition. This information allowed the architect to develop an evidence based refurbishment design approach for this building. A second BPE process post refurbishment evaluated the building performance and provided verification of the design process.

Arisaig is a village located on the west coast of the Scottish Highlands. The LSIC is an $80m^2$ single storey stone construction that sits close to the centre of the village and was originally built as a blacksmiths during the late 1800s (Figure 1). After use as a blacksmiths the building was in private ownership and used as a store. The local community purchased the building in 1999 and refurbished and added three small timber frame extensions. The restored building was in use from 2000 onwards as the LSIC visitor facility and heritage centre, exhibiting information and artefacts relating to the local and surrounding area (Figure 2). The three areas within the building have distinct functions; the main entrance opens into an area used as a reception and a craft and book shop providing a revenue generating stream; the heritage exhibition hall is wholly within the historic part of the building and displays artefacts and the former blacksmiths forge; and leading from here is the room with a view used as a small seminar room and looks out over Arisaig bay.

Figure 1. View of former Smithy, now LSIC building, from the west.

Figure 2. View of LSIC building from the west, facing exhibition, WC extension and room with a view.

In 2011, Arisaig Community Trust (ACT) took ownership of the LSIC and increased visitor numbers from 1,000 to over 10,000 in less than two years. However, the ACT found that they were unable to heat the building beyond 15°C with the electric storage heaters during the winter and due to the expense of the space heating the building was closed from September to April each year, catering mainly for the needs of tourists and the local community for festive events leading up to Christmas. Having successfully applied for and awarded £142,000 grant funding for energy efficiency improvements ACT had employed the services of an architect (Sam Foster Architects (SFA)) to design an eco-refurbishment. The funding also paid for a full-time staff member to oversee the eco-refurbishment as well as promote other energy conservation activities throughout the local region. In the funding application ACT had indicated an ambitious 75% voluntary carbon dioxide emissions reduction from the building based on expected energy reductions. There were no requirements for an energy performance certificate to be provided for the refurbishment of this building, as this type of improvement work was not covered by the building regulations at that time. SFA had intended to benchmark the existing building performance to allow future validation of the reductions achieved, and to ascertain whether the design met the design intent and anticipated reduction target set by the client. There were no requirements to demonstrate the real energy reductions or project impact to the grant funder. The benchmarking process was undertaken through BPE which also took user experiences into account and although BPE had been carried out on retrofit projects, there were no studies found that attempted to evaluate a building in this way both before and after refurbishment.

Building Performance Evaluation (BPE) is used for the assessment of the design, construction and operation of a building and is a systematic process that includes a range of non-destructive quantitative testing techniques relating to the building fabric and indoor environment as well as qualitative surveys. The latter aim to understand user satisfaction and user understanding for control of designed systems. There is no standard methodology for conducting BPE, the method used for this case study were based on methodologies established by the Technology Strategy Board (now Innovate UK) [13]. The data collected as part of a BPE process provides a means for the assessment of the 'as designed' performance against the real outcome in the 'as built' condition, reviewing data against occupant satisfaction levels. This process is normally undertaken in new buildings shortly after occupation and is rarely undertaken on existing buildings. Over recent years, the uptake in

BPE has grown for assessment of the design and construction of new homes in the domestic sector. Despite this BPE is rarely undertaken in existing buildings and seldom for those buildings about to undergo major refurbishment.

The original part of the building comprised unrendered 600mm thick whinstone rubble walls, insulated internally in 1999 with a 100mm timber frame infilled with poorly-fitted glasswool insulation, discontinuous polythene vapour barrier and plasterboard. One existing stone wall had been left un-lined as a ‘feature’. The original earth floor of the building was replaced in 1999 with a tiled concrete slab that extends into the timber-frame extensions. The original timber roof frame was also replaced in 1999, with raised collar timber trusses installed over the original building and extensions. These were also insulated with glasswool above the ceilings, and lined with a discontinuous polythene vapour barrier and lined with tongue and groove wood boards. The existing timber windows were found to be difficult to open, poorly fitting and poorly insulating, resulting in a lack of opening for ventilation of the building and condensation build up. The existing electrical circuits, were installed within the depth of the timber framed wall linings and roof trusses, these were found to be safe and in reasonable condition so were retained. Existing electric night storage heaters were found to be inefficient, incapable of meeting the high heat loss from the building, and requiring replacement.

The general refurbishment strategy was to create a continuous internal layer of insulation inside the existing timber frame wall linings and roof trusses, to reduce heat loss and to buffer internal relative humidity, create a more stable indoor environment for exhibits, reduce air infiltration and improve overall comfort for the building users. Existing floor tiles were removed, the floor slab was levelled and a continuous 15mm layer of aerogel insulation laid over to reduce heat loss through the floor. A linoleum floor finish was then laid over. The existing plasterboard and polythene linings inside wall framing and roof trusses were removed. Existing glasswool insulation was re-packed and topped up as necessary to infill any voids. On the internal face of the insulated wall linings and trusses a continuous, 100mm thick layer of rigid woodfibre insulation was installed, with the tongued and grooved edges of the woodfibre helping to reduce draughts; all joints were fully taped to prevent draughts. This insulation treatment was extended to the exposed stone wall, creating a continuous layer of insulation around the whole building. Fermacell wallboard was fitted to the internal face of the walls and roofs. To prevent condensation from occurring and accumulating at the inside face of the original stone walls, holes were drilled externally through the base of the stone walls. This created a ventilation path outside of the airtight envelope between the base of the walls and the head of the stone walls. High quality, triple-glazed, timber framed windows were installed, with easy-to-operate handles and mechanisms. Electrical cables passing through the woodfibre insulation were sealed with proprietary airtightness 'grommets' to prevent draughts entering at these points. New energy efficient display lighting was installed, together with more energy efficient and responsive electrical heaters.

In the future, the ACT aim to increase the floor area of the LSIC to include a café, this will involve the replacement of the reception/shop extension. Therefore, the reception/shop area underwent minor refurbishment and redecoration. During the 1999 works a coat of white painted cement render was applied externally over the building, unfortunately the removal of this and replacement with lime render was not permitted under the energy efficiency grant funding. The continued fundraising activity by the local community will also support future render replacement works.

This paper highlights the design decisions made when designing for the energy improvement of this case study building. The BPE uses qualitative and quantitative methods and non-destructive testing to investigate the building performance between pre and post refurbishment stages of this existing community building. The initial BPE monitoring was funded by the Scottish Funding Council and undertaken over a month long period in 2014. The eco-refurbishment took place from January 2015, completing in June 2015. Following this, post refurbishment monitoring was completed during 2015 with grant funding from Zero Waste Scotland. From here forward the 2014 pre-refurbishment BPE will be referred to as PERIOD 1 and the post-refurbishment BPE carried out in 2015 will be referred to as PERIOD 2.

2. METHODOLOGY

A mixed methods approach was conducted for the BPE, which were identical for both PERIOD 1 and PERIOD 2. The initial monitoring (PERIOD 1) took place through the entire month of December 2014 to ascertain the existing building performance and to utilise these results to influence the architectural design intent for an energy efficient refurbishment. Following completion of the refurbishment, PERIOD 2 monitoring was conducted throughout December 2015, to assess the success of the energy efficiency improvements and to determine whether the 75% energy reduction target was achieved when compared with the pre-refurbishment condition.

2.1 SEMI-STRUCTURED QUESTIONNAIRE

A semi-structured questionnaire was used for all those employed and volunteering at the LSIC at the time of surveys. In total, six were completed for PERIOD 1 and five for PERIOD 2. The questionnaire consisted of a series of questions designed to attain occupant perception of their comfort levels and user understanding for effective building operation. A seven point scale was used together with an option for comment on each set of questions.

Completion of these was at the start of the monitoring by face-to-face interviews with the two employees at the LSIC, these took approximately 30-45 minutes. Those who volunteered their time at the LSIC, completed their questionnaires independently.

2.2 AIR PERMEABILITY TESTING WITH THERMOGRAPHY

Air permeability testing of the building was conducted in accordance with the Air Tightness Testing & Measurement Association (ATTMA) Technical Standard L1 (TSL1) [14] using calibrated equipment. A range of test values were recorded while the building envelope was under both positive and negative pressure, where the overall outcome is an average of these two measurements. In addition, once the induced negative pressure differential was stabilised a smoke pencil was used within the building to trace areas of air leakage within the building. Further air leakage detection utilised infrared thermography for indication of air movement behind finished surfaces. This was undertaken by a qualified external contractor.

2.3 IN-SITU U-VALUE MEASUREMENTS

The in-situ u-value measurements were recorded for four separate building elements: one ceiling element, an insulated external wall in two separate locations, and an uninsulated external whinstone wall with rubble core. The methodology for measurement and subsequent analysis followed the procedures outlined in ISO9869:1994 [15]. However, due to the orientation of the building, it was not possible for all measurements to be on north facing elements, therefore apparatus was installed to an east facing ceiling, two east facing insulated walls and one north facing stone gable. Data readings were taken using calibrated equipment consisting of: Hukseflux heat flux plates (HFP01) with wired connections to Eltek GS44 voltage input transmitter, type UU thermistor sensors with wired connections to Eltek type GD32 -50 to 150°C transmitter, Eltek type OD12 external temperature transmitter. Readings were transmitted to an Eltek RX250AL radio telemetry data logger set to log at 5 minute intervals.

2.4 ENVIRONMENTAL MONITORING

Internal temperature and relative humidity readings were taken in four separate locations in the building, using high accuracy Tinytag Ultra 2 TGU-4500 indoor dual channel data loggers (accuracy < 0.5°C and ± 3% RH at 25°C). Internal carbon dioxide concentrations were recorded using Tinytag TGE-0011 (accuracy < ± 50ppm =3% of measured value) these were set up adjacent to the Tinytag TGU-4500 data loggers. External temperature and relative humidity measurements were monitored using Tinytag Plus 2 TGP-4500 waterproof temperature and relative humidity loggers (accuracy < 0.5°C and ± 3% RH at 25°C). Through the assessment period, each of these data loggers were set to simultaneously log at 5 minute intervals. Figure 3 shows the location of monitoring apparatus for PERIOD 1 and PERIOD 2.

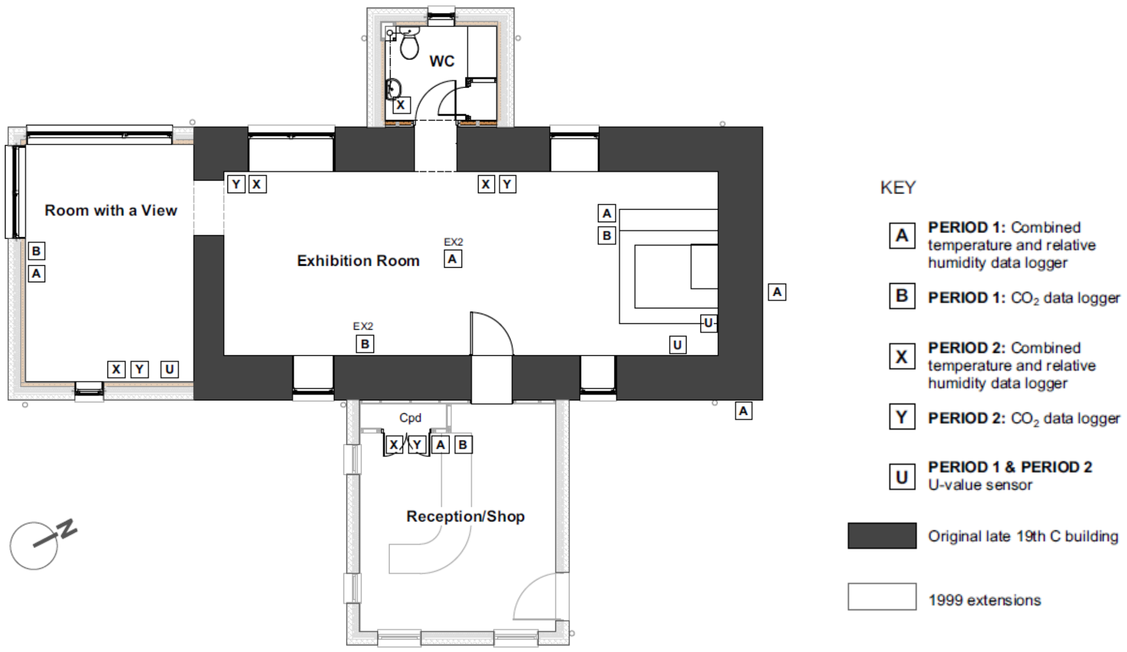

Figure 3. Plan view of LSIC building, indicating the historic core, 1999 extensions and location of monitoring apparatus for PERIOD 1 and PERIOD 2 BPE.

2.5 ELECTRICAL METER READINGS

During PERIOD 1 the staff at the LSIC manually recorded the electrical energy consumption from the two existing meters (space heating and mains) twice each day; recording these when opening the building and again on closing for the night, when the building was closed through the daytime the readings were still taken twice each day at the same times. During the refurbishment the space heating meter was removed and therefore the PERIOD 2 monitoring used the Arisaig Community Trust's (ACT) OWL energy monitor (http://theowl.com/) for recording the space heating consumption. This monitor was display only and a daily manual record was kept by the LSIC staff twice per day as with PERIOD 1. The mains electrical consumption data were recorded directly from the meter and a separate Efergy 'engage' energy monitor was clamped to the lighting circuit. The data for this was remotely collected through the Efergy web application (https://engage.efergy.com/).

3. RESULTS

In order to facilitate the design process for the refurbishment of the LSIC, the building was subjected to a range of non-destructive testing techniques, and semi-structured questionnaires were used with the occupants to gauge their satisfaction and comfort levels with the existing building (PERIOD 1). After the refurbishment, a similar BPE exercise was conducted to determine the success of the refurbishment strategy (PERIOD 2).

3.1 QUESTIONNAIRES

Semi-structured questionnaires were undertaken with the two LSIC staff members and those that volunteered at the LSIC. Respondents were asked to respond to a series of questions that related to their perception of the internal environment, building operation, and the handover process.

In PERIOD 1 all six respondents indicated that the heat emitters were on 24 hours per day during winter and the settings were set by the LSIC manager. Two respondents had indicated the need for additional heating to boost the temperature and one had stated that "*we just bulk up and put layers on*". None of the respondents had perceived the building to have been too warm or overheated. Windows during the winter season were not opened by any respondents and windows were "*very rarely"* opened during the summer. Despite most respondents "*find*[ing] *the building too cold in winter*", half of the respondents were satisfied overall with their perception of the thermal comfort during winter and all were comfortable during the summer.

When asked about the indoor environment four of the respondents had noticed condensation on windows, two had noticed mould growth on the window frames. In all cases, the participants were unaware of the running costs of the building and only two had received some training on how the systems in the buildings were controlled and operated.

A number of key themes were identified, particularly with the winter condition, these were that the building was inadequately heated, occupants were cold and experienced discomfort, there was no engagement with heating system controls, occurrences of condensation, lack of ventilation and no formal handover process.

In PERIOD 2, of the five respondents, three knew what type of heat emitter had been installed. There was one person responsible for programming the settings, and of the seven heat emitters only three were used regularly during winter as the users found the building warm enough and the heating responsive. The respondents had expressed their satisfaction with the thermal environment where one had indicated "*the building is very comfortable*". But two had noted that the building can get slightly too warm in winter and summer. Other than this, in response to problems relating to thermal comfort only one interviewee commented that the building can get too warm if the 'auto' mode is used for the building, adding that the default temperature for this mode is 22°C.

Window opening patterns had not changed since PERIOD 1, where windows were not opened during the winter months, however, trickle vents were now used. Condensation was noted by two respondents; this was restricted to the window in the reception/shop area which was not replaced during the refurbishment.

Three people had detailed knowledge of how all the systems were operated, these were the staff members and the centre manager. One respondent had commented that a quick start guide to the building that had recently been provided by the architect was helpful. The themes identified were a warm building with controllable heating, condensation remaining an issue in the un-refurbished area, lack of ventilation and that not all of the volunteers had received information on how to operate the building.

Overall these results provide important insights into building operation and user perception. It is of concern that the windows are not operated during the winter to provide adequate ventilation. Feedback was provided to the architect and client that suggested more guidance is given as to the correct ventilation and heating protocol.

3.2 AIR PERMEABILITY

The air permeability was tested in order to identify the areas of air leakage, insulation installation and areas where thermal bridges occurred and were therefore at risk of condensation and mould growth. The results for PERIOD 1 revealed the building to have excessive infiltration levels of 16.76 $m^3/h.m^2$ @ 50Pa (Table 1), which had caused significant discomfort for the occupants through draughts. Tracing the air leakage pathways, using smoke pencil and infrared thermography highlighted locations in the building where air leakage was the most severe. These were most notably where the three extensions and replacement roof (added in 1999) connected to the existing stone building (Figure 4). The most significant air entry points were at all joist ends, mains electricity incoming cable and the soil vent pipe adjacent to the WC. In addition, the infrared thermography identified areas of incomplete insulation, where a consequence of this was localised cooling and an increased risk of condensation.

Table 1. Air Permeability measurements PERIOD 1 and PERIOD 2

Test	**Air Permeability Measurements ($m^3/h.m^2$ @ 50Pa)**		
	Negative	*Positive*	*Mean*
PERIOD 1	16.76	19.32	18.04
PERIOD 2	2.61	2.79	2.70

The PERIOD 2 air permeability test result of 2.7 $m^3/h.m^2$ @ 50Pa (Table 1) was extremely low and is now lower than the Building (Scotland) Standards current regulations for new buildings of 7.5 $m^3/h.m^2$ @ 50Pa [9]. Moreover when compared with the results from PERIOD 1, the thermal improvements and attention to the design detail by the contractor have reduced uncontrolled infiltration by 85%. The testing provided confirmation of the architects' refurbishment approach, however, air leakage in the shop area was found to be higher than other areas in the building. Aligning with the refurbishment strategy, where minor refurbishment was made in the shop, with demolition and a replacement extension planned for the future.

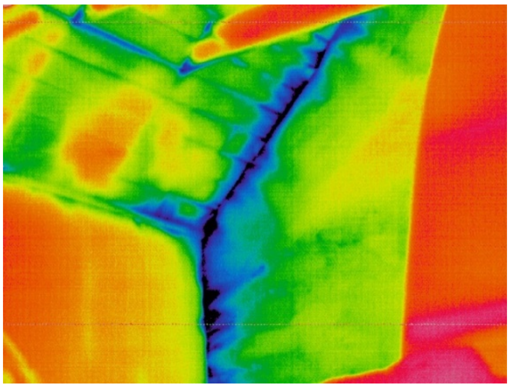

Figure 4. Thermogram of the uninsulated north gable junction with the insulated west wall and ceiling. This indicates significant air leakage at joist ends, cool spots behind timber ceiling and air ingress at the corner.

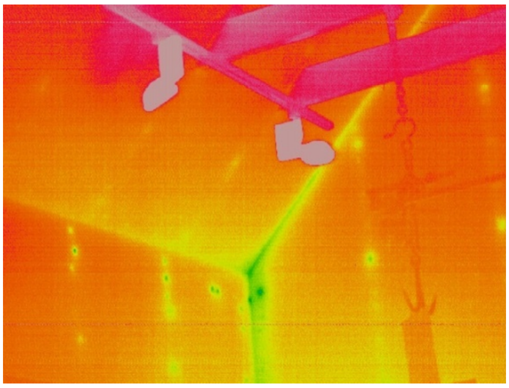

Figure 5. Thermogram of where the newly insulated and lined north gable junction with re-insulated west wall and ceiling. This indicates no cooler areas at joist ends, and a slightly cooler area at the corner.

3.3 IN-SITU U-VALUE

Measurements of in-situ u-values were undertaken for four opaque building elements. These were undertaken in PERIOD 1 to assess the existing thermal performance in order to support the refurbishment decision making for thermal envelope improvements. Table 2 presents the calculated results derived from PERIOD 1 and PERIOD 2 measurements alongside the regulated minimum elemental u-values for the opaque elements added in 1999 and manual steady-state calculations made by the architect based on 'as built' drawings and the thermal properties of the materials indicated in these.

Table 2. Comparison of predicted u-value with PERIOD 1 and PERIOD 2 measured u-values W/m^2K

Surface	Room	Building Element	Orientation	1999 Elemental u-values	Architect Manual u-value	In-Situ u-value PERIOD 1	In-Situ u-value PERIOD 2
A	RWV	Ceiling	East	0.20	0.43	0.72	0.26
B	RWV	Lined wall	East	0.30	0.49	0.40	0.22
C	Exhibition	Lined wall	East	0.30	0.49	0.25	0.21
D	Exhibition	Stone wall	North	n/a	1.64	0.93	0.40

Comparison of the physical measurements made in PERIOD 1 against the manual calculations highlight that inaccurate u-value assumptions were made as part of the design process. These were underestimated for surface A and overestimated for the remaining surfaces. However, surfaces A, B and C were introduced as part of the extension works in 1999 where only one (Surface C) complied with the minimum standard at that time. The measurement process was repeated in PERIOD 2, confirming that significant u-value improvements were made of 63%, 45%, 16% and 57% in building elements A, B, C and D respectively.

3.4 ENVIRONMENTAL MONITORING

This analysis examined the external and internal air temperatures in order to assess whether there was a correlation between energy consumption for space heating and occupants self-reported thermal comfort status. Monitoring of the internal carbon dioxide concentrations were undertaken to assess provision of ventilation. Each of these parameters were recorded at five minute intervals for both monitoring periods.

3.4.1 Air Temperature

The external temperature throughout both monitoring periods was unseasonably warm for the time of year. Figure 6 presents an overview of the temperature ranges through two monitoring periods where median external air temperature was around 6°C and 7°C for PERIOD 1 and PERIOD 2 respectively. There were similar weather patterns during both of the monitoring periods with unexpected warm days, during which the external temperature rarely fell below 0°C. However, when comparing internal air temperature data for both PERIOD 1 and PERIOD 2 significant differences were observed. In PERIOD 1 the internal temperature distribution is relatively wide with the majority of internal temperatures remaining between 11-15°C. Conversely, the comparison of data between PERIOD 1 and

PERIOD 2 indicates higher internal air temperatures for PERIOD 2 that are relatively stable between 16-18°C in each of the three monitored rooms.

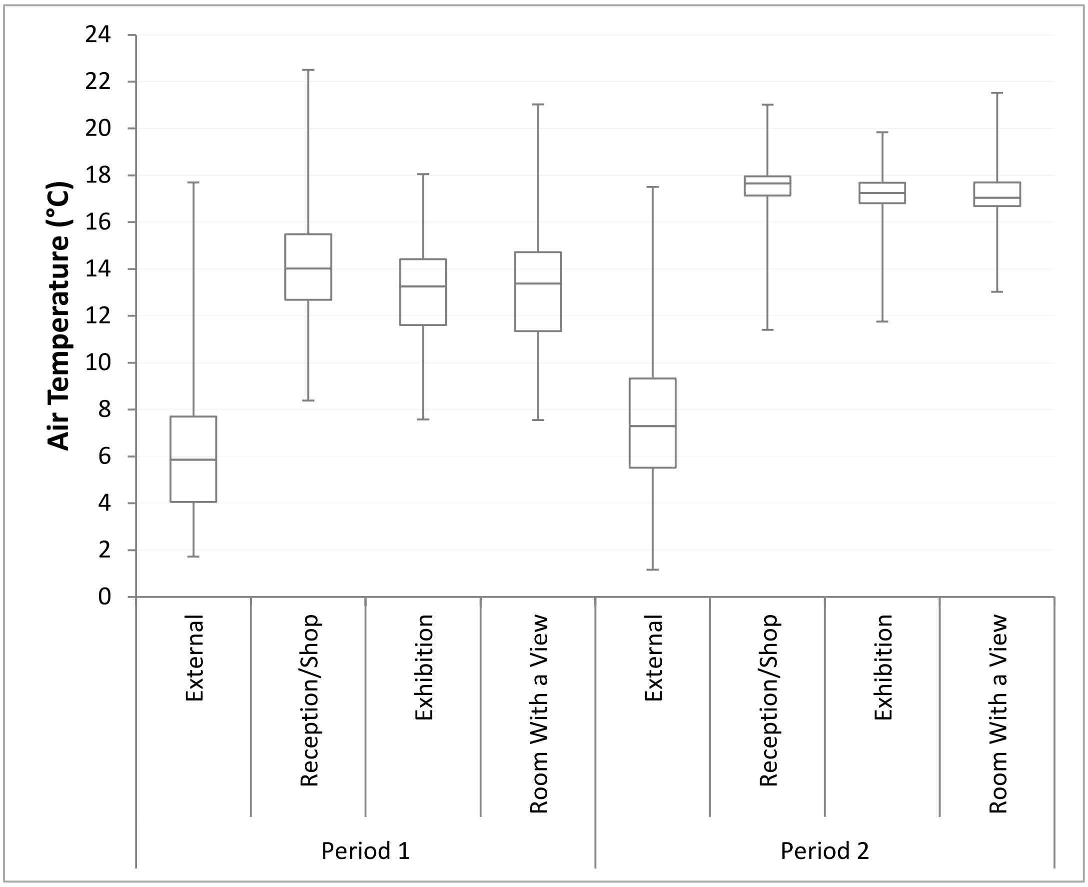

Figure 6. Overview of PERIOD 1 and PERIOD 2 temperature (˚C) ranges.

3.4.2 Relative Humidity

External relative humidity (RH) readings were wide ranging, with the bulk of external data between 75 and 98%. While the RH data in Figure 7 indicates that PERIOD 2 was slightly less humid than PERIOD 1, when correlating between external temperature and RH on a psychrometric chart the external moisture content for both monitoring periods are similar. The indoor monitoring indicated the RH remained between 30-70% with the median at around 50-55% RH for PERIOD 1. Comparing this data with PERIOD 2 there is a distinct difference where lower RH was recorded and RH conditions were more stable.

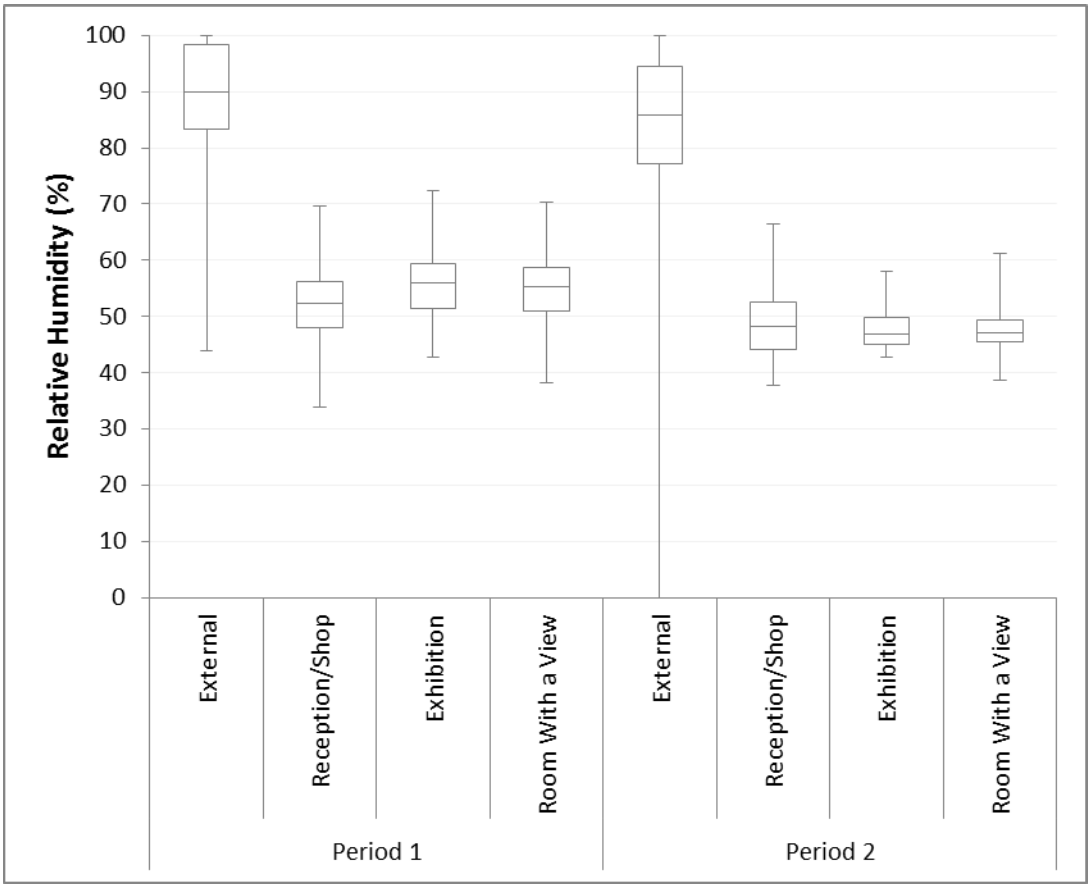

Figure 7. Overview of PERIOD 1 and PERIOD 2 relative humidity (%) ranges

The reception has the largest fluctuations; however, this was an expected outcome due to the cosmetic upgrade designed for this area. The exhibition room indicated a narrow RH band showing less of a RH swing. This type of behaviour is favourable for the exhibits on display and aligns well with the recognised RH band for health of buildings and occupants. Furthermore, there were no significant differences in overall internal moisture content, and therefore the more stable conditions could be a result of the quantity of vapour open building materials used in this room.

3.4.3 Indoor Air Quality

Carbon dioxide concentrations were measured to allow evaluation of the ventilation rates within the building. A comparison of PERIOD 1 and PERIOD 2 concentration rates were made for all three monitored rooms and were additionally compared against established benchmarks. There were unexpected differences in concentration rates where PERIOD 2 had higher peaks than PERIOD 1 in concentrations during the two monitoring periods. The data plotted for the room with a view (RWV) in Figure 8 indicates that there were large peaks and troughs in carbon dioxide concentrations over three consecutive days during both monitoring periods and similarly with the reception/shop area results in Figure 9. These peaks were later associated with Christmas fair events that were well attended by the local community. Aside from this annual event, what is interesting about the data is that there were frequent carbon dioxide concentration increases, most notable during PERIOD 2 monitoring. While these peaks have been taken to be within acceptable carbon dioxide concentration limits, of less than 1,000ppm, for acceptable indoor air quality, a theme is emerging where the building may not be being adequately ventilated when occupied.

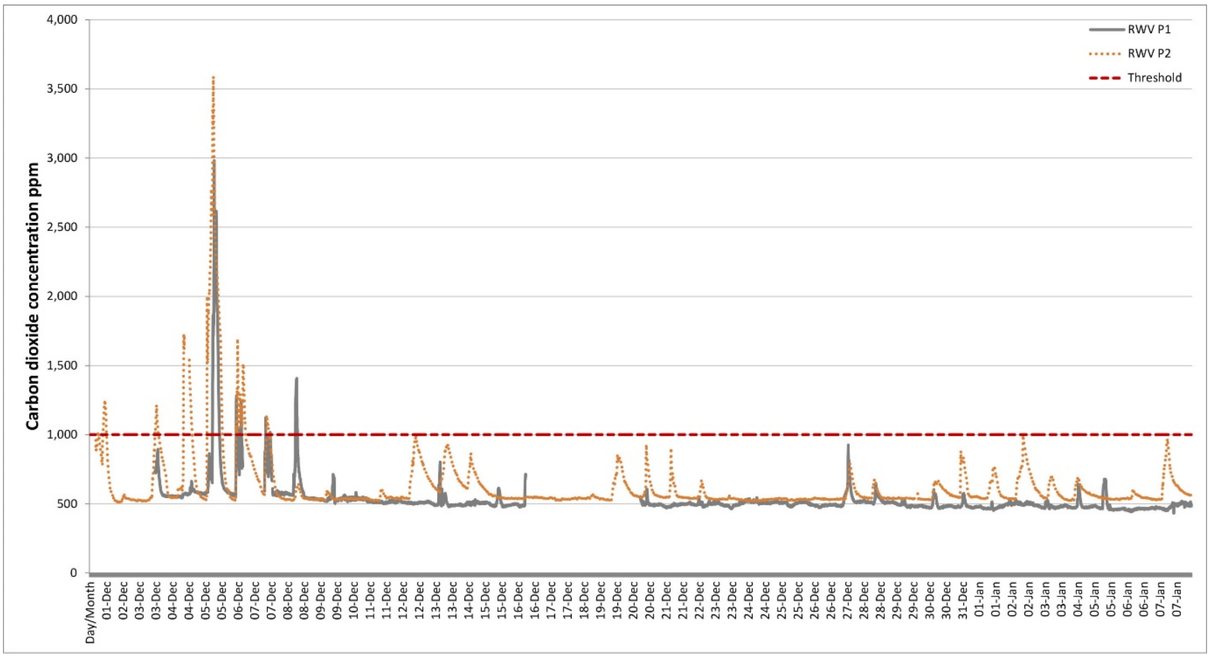

Figure 8. Room with a view (RWV) Carbon Dioxide (CO_2) concentrations throughout PERIOD 1 and PERIOD 2.

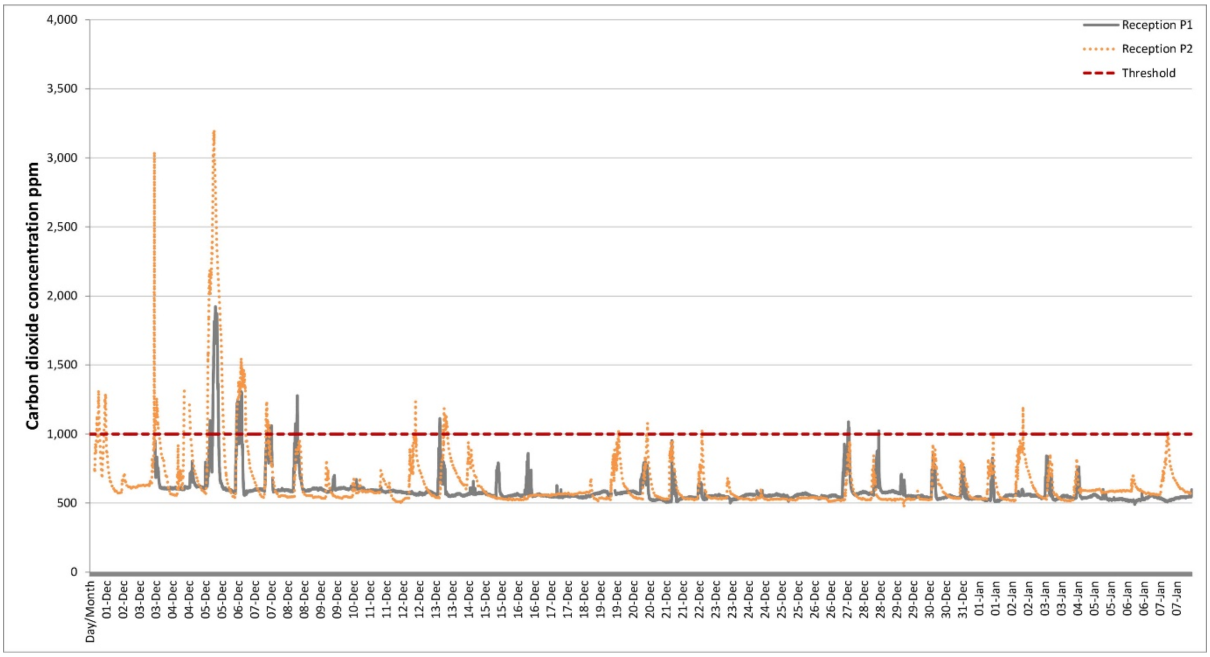

Figure 9. Reception/shop area Carbon Dioxide (CO_2) concentrations throughout PERIOD 1 and PERIOD 2.

3.5 ELECTRICAL

Electrical meter readings were recorded twice each day and this information was used to assess the overall energy reductions in the building. Figure 10 indicates a significant overall energy consumption reduction of 57% between the two monitoring periods. This is 18% less than the 75% prediction. However, the building occupation increased from around six months opening per year before the refurbishment to twelve months opening per year after the refurbishment (PERIOD 2) which affects the overall energy reduction.

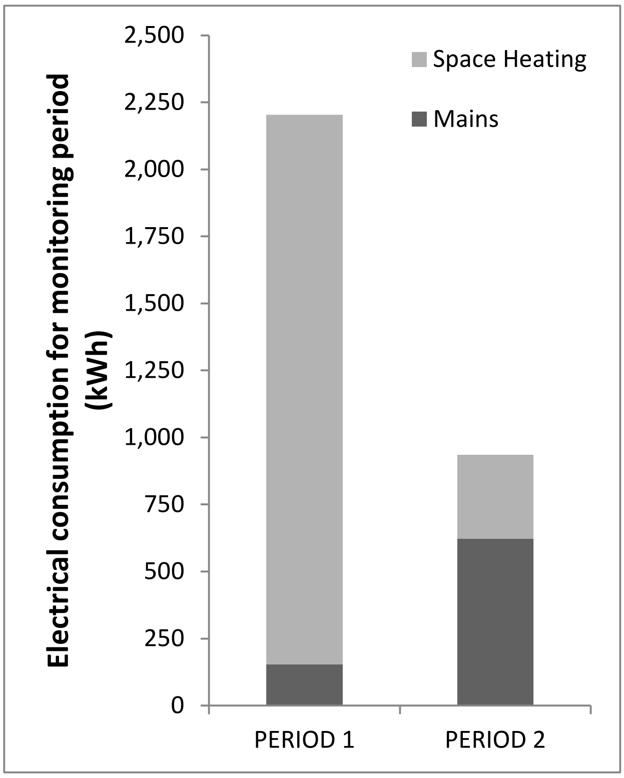

Figure 10. Overall energy consumption, space heating and mains, in PERIOD 1 and PERIOD 2.

The most surprising aspect of this data was the unexplained dramatic increase in mains electrical energy consumption between the two monitoring periods. Post PERIOD 2 BPE the LSIC employed the services of an electrician to determine the cause of the unexpected increase in mains power consumption. It was found that two of the electric storage heaters had been incorrectly wired to the mains small power circuit. Knowing this is of future benefit should separate energy meters and tariffs be introduced in the future.

Since the monitoring took place the LSIC have provided two data sets containing annual energy consumption, carbon dioxide emissions and expenditure for the financial years covering both monitoring periods (Table 3). This data clearly indicates an overall energy consumption reduction following the refurbishment. However, it is important to highlight the opening hours in PERIOD 2 have increased by six months compared with PERIOD 1.

Table 3. Comparison of annual energy consumption, carbon dioxide emissions and energy cost

	Energy Consumption (kWh)	**Energy Consumption per unit floor area (kWh/m^2)**	**Carbon Dioxide Emission ($kgCO_2e$)**	**Annual Cost (£)**
PERIOD 1 May 2014 – May 2015	11,566	145	4066	1,344.61
PERIOD 2 May 2015 – May 2016	7,448	93	2618	1,171.28

4. DISCUSSION

The initial objective of the study was to establish through BPE the energy performance of the case study building (LSIC) to provide robust ‘as existing’ information to inform an appropriate and energy efficient retrofit strategy. This strategy was funded by a Scottish Government grant, the application for grant assistance was rigorous, requiring detailed calculations for carbon dioxide emission reductions. However, there were no mechanisms in place that required the applicants to prove the baseline evidence nor report the actual reductions achieved, where in theory there could be a performance gap. BPE post-retrofit for determination of the ‘actual’ performance is rarely undertaken, where the ‘predicted’ reduction in carbon dioxide emissions are usually taken as the measure of success, which can entirely contrast with real outcomes. The small size of the LSIC meant that lessons learned for energy reductions could be applicable to traditionally constructed dwellings in the local area. Therefore, the 'actual' performance for verification of the design approach was fundamental to the overall success of the project, where the outcomes can help the local community begin to understand the complexity involved in refurbishment approaches for their similar traditional buildings.

The energy performance was evaluated using a BPE method that required systematic collection and cross-referencing of a number of data streams. This enabled a holistic understanding of the existing building performance and importantly the building user comfort perceptions and how they operate the building. PERIOD 1 monitoring provided benchmark data for PERIOD 2 monitoring results to be compared against and for quantification of the 'actual' energy efficiency improvements made.

Responses from the semi-structured questionnaire for PERIOD 1 identified that all those working within the building reported thermal discomfort in the heating season. Their statements closely correlated with the internal air temperature measurements which rarely exceeded 15°C during the monitoring period, unless supplementary 'plug-in' heat sources where introduced. The relatively warm external temperatures for the time of year had little impact on the internal temperature and due to high heat loss from the building there was a need for heat emitters to operate 24 hours per day, yet temperatures were not sufficiently raised to improve thermal comfort. Despite indoor temperatures being lower than the health and safety executive lower temperature threshold for workplaces of 16°C, the workers adapted their clothing and wore outdoor coats inside to allow them to work in this environment for short durations of the year. It was unsurprising that the staff did not open windows to ventilate the building due to fear of lowering the temperature further.

These low temperatures posed a decay risk to the building fabric, where consistently low internal surface temperatures could give rise to condensation and mould growth within the building and its fabric. Due to the cold internal environment the building and the high costs associated with electric heating, the building closed outwith the summer tourist season, like many other businesses in the local area. This affected social interaction among the local community and also posed a potential threat to their mental health and wellbeing.

The BPE process improved the building fabric in two ways; these were the setting of a set of benchmarks for future comparison and the identification of key areas that required particular design attention. The analysis of the buildings' air permeability and in-situ u-value measurements returned unexpected results that directly influenced the architectural design approach with regards to airtightness and the insulation envelope.

The architect had previously developed an airtightness strategy for the building, however, the extent of air leakage pathways identified were unexpected. There were significant infiltration pathways at the vertical junctions associated with the later building additions, as well as at both ends of the exposed roof trusses, also added in 1999. These weak points in the building fabric provided a means for unheated outside air to infiltrate the building, move freely behind the plasterboard and timber lined ceilings, entering the building at joist ends, sockets outlets and light switches which were detected in the building as draughts. In response to this the architect developed a sealing method for these using flexible vapour open building materials and added these to the drawings which identified a need for one single person from the contracting team to be an airtightness champion.

During the refurbishment pre-start meeting the architect communicated the evidence based airtightness strategy and indicated areas where particular attention was required. The infrared thermography undertaken with the air permeability test indicated that there was missing or poorly fitted insulation behind plasterboard surfaces. The removal of finished surfaces on internal walls was included as part of the refurbishment strategy to improve the quality of fitting of the existing insulation. The PERIOD 2 monitoring indicated that an overall air permeability improvement of 85% was made. Thermograms taken during the PERIOD 2 test revealed a vast reduction in thermal bridges that were a result of the architects detailing strategy, combined with good quality workmanship. While the staff did not know what this meant they all noticed a lack of draughts in the refurbished building, and commented on how warm the building was.

It is noteworthy that the comfort temperature for the staff is 18°C, which is lower than the expected comfort temperature of 19-21°C. This could be that the lack of draughts may contribute to the volunteers being more content with their thermal environment. It is also significant that most of the volunteers live locally in draughty old houses, one volunteer now spends time in the LSIC room with a view to keep warm and read a book when not working.

Prior to the PERIOD 1 BPE the architect had based the insulation envelope design on recognised manual steady-state calculations based on 'as built' drawings and using best practice thermal properties for the materials indicated. The steady-state calculations revealed poorer results than what were bound by the building regulations at that time; these poorer u-values formed that basis for the refurbishment design. Surface A and B were located in the room with a view extension added in 1999 and surfaces C and D were located within the exhibition room in the original stone building, surface C had been internally insulated and plasterboard lined in 1999 and surface D was the stone gable of the original building.

Comparing the PERIOD 1 measurement results to the design u-values the thermal performance of each wall element was better than anticipated, in particular surface C and D where u-values were 50% and 43% respectively lower. Surprisingly the ceiling/roof element thermal performance was 40% poorer.

These findings allowed the architect to reduce the thickness of the proposed woodfibre internal insulation for the walls and increase thickness of the roof insulation, which was cost neutral to the project. The difference between the steady-state calculation and the real situation gives rise to concern, while it is recognised that in-situ measurements may not be practical in every situation, the inconsistency in the two sets of results indicate these best practice thermal properties are outdated. Should a designer be aiming to achieve a particular u-value, thermal insulation levels may be increased beyond the critical thickness, resulting in interstitial condensation and potentially cause irreversible damage to the building. This may have significant consequences to traditional buildings, and more case study information is required to reach the mainstream builders and current custodians of our built heritage.

Materials, finishes and paints were carefully selected for their vapour open properties that improved the hygrothermal performance of the building. The testing of this was outwith the BPE scope, however the more stable RH results suggest the hygroscopic building materials applied in the exhibition room and the room with a view were of some benefit to the indoor environmental conditions and this warrants further research to evaluate this.

Contrary to expectations the PERIOD 2 monitoring indicated that there was the lack of engagement with the ventilation strategy, where the staff and volunteers continue to keep windows closed during periods of cold weather. A consequence of this is periods of poor indoor air quality at times of high occupancy. The former window opening habits from the previous building condition have continued in the refurbished building. This had been highlighted to the architect as a potential risk post PERIOD 1 monitoring. In an effort to overcome this, the architect produced a simple user-guide booklet of the building that included the designed ventilation strategy (window opening). This booklet is now kept at the reception desk and once the PERIOD 2 results were explained to LSIC staff there was a genuine intent to open windows more frequently by the staff. The subject of controlling ventilation in this building raises intriguing questions regarding habit forming and the challenges faced for behaviour change following a building retrofit after many years of operation in one condition. Two years on, it remains unknown whether the staff have followed the ventilation guidance, and a future investigation of the indoor air quality is recommended to develop a full picture of the buildings operation.

In respect of the overall energy savings, the intended target of 75% reduction was not achieved, some would argue that a 57% reduction fell some way short of the design intent. However, an unexpected outcome discovered while undertaking the PERIOD 2 monitoring was the buildings extended opening hours from six months to all year round as a result of the upgrade works. In addition to this, the centre has become a valuable community hub, with evening film screenings, music groups and other local informal gatherings.

Since the BPE and refurbishment project a new document BS EN 16883:2017 [16] has been published, this document describes an evidence-based approach for refurbishment of all historic buildings. The methodology includes selection of reversible appropriate building materials, as with this project and also identifies a period of monitoring during the design phase extending to post refurbishment post occupancy evaluation (POE) once works are completed. While this is a useful document aimed at safeguarding the built heritage and contains many similarities to the process adopted for the recent refurbishment of the LSIC, more information is required for those commissioning and undertaking BPE. It is important for the BPE to be carried out by an independent trained BPE professional that uses appropriate calibrated equipment.

5. CONCLUSION

This paper presented a case study traditional building which was about to undergo refurbishment for 75% carbon dioxide emission reductions. However, the existing performance was unclear, therefore BPE was undertaken to understand how the building performed and to set benchmarks for post-refurbishment comparison. There were two goals firstly to quantify the success of the refurbishment in energy efficiency terms and secondly to use the building as a teaching tool for the local community to learn about principles of refurbishment of similar building typologies. This is important in Scotland as many traditional buildings define the local character of an area, provide cultural identity and sense of place. This is of particular importance in rural communities, such as in Arisaig, that are reliant on tourism for many employment opportunities. Further to this with the Community Empowerment (Scotland) Act 2015 [17] the trend for the purchase and upgrading of traditional buildings for community use is likely to increase as community groups seek to reduce running costs.

The 57% carbon dioxide emission reduction from the building was considered a success, particularly once the wider social benefits became apparent. The LSIC became a warm and welcoming building that can now be opened year round as a result of affordable and controllable space heating. The unexpected wider community impact became apparent as the building now offers and provides a meeting place for locals who might otherwise be lonely during the long dark Scottish winters.

The sensitive and appropriate refurbishment of this small traditional building has the potential to provide clear, relevant information to homeowners who are considering improving the energy efficiency of their own similar homes. However, a wider distribution of information to support energy efficiency improvements should be easily available for owners of listed and non-listed traditional buildings.

This case study demonstrated that Pre- and post-refurbishment BPE of the traditional building stock can provide beneficial information to help inform the refurbishment creating significant energy savings within budget and a comfortable, healthy space for users. This technique requires further development, including a method for making these assessments available and affordable to the general public. This holds great potential as a tool for effective sustainable refurbishment and would go a long way towards preserving the sense of identity and richness of the historic built environment.

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