One year temperature and heat pump performance for a micro-community of low carbon dwellings, in Wales, UK

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Abstract

This paper discusses some of the findings from an InnovateUK funded Building Performance Evaluation programme project, which finished in 2015, at a micro-community, of Low Carbon Dwellings in Wales, UK. The paper focusses on the 12 month (July 2013 to June 2014) monitoring of the buildings, in terms of temperature (external and internal) and performance of the heating systems. The case study micro-community consists of nine and four low impact single storey flats and two storey houses respectively. All the units at the scheme use exhaust air source heat pumps (EASHPs), deemed by their manufacturer to be smart efficient heating systems which are used extensively in Scandinavia to provide hot water and space heating needs, coupled with underfloor heating. The EASHP is a heating system that supposedly requires little human intervention for sustainable operation. The project monitoring and reporting completed in 2014 and 2015 respectively, and the findings discussed in this paper demonstrate that the installation, commissioning, operation and maintenance of the EASHPs has not been as-designed, such that a Performance Gap exists and is less than ideal for a sustainable future. Indeed, the weaknesses are multi-facetted including foremost the thermal performance of the component elements. This paper will be of interest to building services engineers, architects, housing associations, developers, building contractors, academics, policy makers and the manufacturer of the EASHP.

Keywords: Building Performance Evaluation (BPE); Energy & Environmental Monitoring; Low Carbon Dwellings, UK, Performance Gap.

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1. Introduction

This paper discusses some of the detailed energy and environmental monitoring findings from a Building Performance Evaluation (BPE) project for a micro-community of low carbon dwellings in Wales, UK; for the period 2012 to 2015. The project was part of the five year (2008-2015) BPE programme across the UK, which investigated the impacts of innovation in building fabric, heating, ventilation, lighting and controls upon smart low to zero carbon domestic and non-domestic buildings [1, 2]. Two types of projects were funded, those within six months of completion and habitation or use, and those from six months to two years of habitation and use. All Projects were completed by 2015 and reported upon from 2011 to 2015, and the analysis of projects available from early 2016 [2]. The BPE programme was industry led and funded partly by InnovateUK (formerly Technology Strategy Board) and one industry organization, per project; and on some project numerous stakeholders [ibid]. The BPE monitoring included seven mandatory categories, including: design, construction and environmental assessment comparison with as built dwellings; fabric testing, with air permeability, heatflux and thermography tests; review of the construction and client handover to dwelling occupants; post occupancy attitude surveys; review of services and the commissioning process for heating and ventilation; monitoring of environmental performance, energy use versus climatic conditions and other technical issues [ibid].

The project documented in this paper was part of the final tranche of funding from 2012 and started in October of that year, with all monitoring completed by August 2014 and reporting by December 2015 [2, 3]. The project’s industrial partner was one of Wales’ leading developers and owners of affordable housing, known as social housing in the UK [3]. The paper focuses on the results and key messages from the 12 months monitoring specific to external and internal temperatures and the performance of the exhaust air source heat pumps (EASHPs) between July 2013 and June 2014. The paper begins by setting into context the need for conducting BPE projects in the UK, specifically related to the lessons that can be learnt to ensure that new dwellings which use supposedly smart technologies can meet their designed energy reduction targets in use. This is followed by a discussion of the case study in the Welsh micro-community. The methodology adopted to conduct the energy and environmental performance monitoring versus climatic conditions and other technical issues at the case study task is discussed. There is a detailed discussion and presentation of the monitoring results and the technical issues related to the EASHP performance for the 12 month period for one of the dwellings.

2. Energy use in the UK domestic sector

In the UK, domestic heat energy usage contributes 23% of the UKs energy demand [4]. Space heating energy usage has increased by 25% from 1970 with 90% of UK dwellings heated by central heating systems; whilst hot water consumption has decreased by 12% for the same period reflecting changing occupancy patterns [ibid]. For on-grid gas consumers, an estimated 15% of UK households are deemed to be in fuel poverty, this increases to 32% for households’ off-grid using other fuel types, oil, electricity and LPG as the main heating source. Domestic cooling accounts for only 1% of domestic energy usage though this is predicted to rise with climatic change impacts. Even under the current (2016) UK Governmental policies for energy efficiency the domestic demand-side for heating, water and cooking is estimated to be around 500 TWh per year. The Carbon Plan 2011 required a reduction in carbon emissions from heating buildings to near zero in order for the UK, to meet its obligations in cutting greenhouse gas emissions by 80% by 2050. The current use of natural gas, oil and other high-carbon fuels requires alternative ways to heat dwellings as detailed in the UK Government’s ‘The Future of Heating: A Strategic framework for low carbon heat in the UK’ setting out the challenge for de-carbonising heat by 2050 [ibid].

Within the ‘Strategic Framework’ cost-benefits and uncertainty over industry standards are coupled with a lack of consumer awareness of new heating technologies, disruption and reliability of smart systems, under developed supply chains, lack of skill base and consumer behavior, which are highlighted as the key barriers to reducing heat energy demands [5]. Within the mature market for boiler technology with cost benefits achieved through mass production, the costs associated with low carbon heating technologies is a significant barrier in consumer choice [6]. New housing in the UK therefore represents one of the easiest sectors of the domestic economy to implement carbon-emission reductions cost-effectively and in 2007 the UK Government announced its intention for all new homes to be built to a zero carbon standard from 2016 [7]. The performance targets of the zero carbon standard are being implemented
through progressive strengthening of the requirements of Approved Document L1A ‘Conservation of fuel and power in new dwellings’ (ADL1A) of the Building Regulations [8].

Energy demand for heating, (and cooling), is dependent on the difference between external and internal temperatures which currently is addressed within building design by regulatory requirements to significantly reduce the air permeability of a building. Making a dwelling more airtight helps to reduce heat loss; but a high air tightness level increases the need for ventilation to improve indoor air quality. Mechanical ventilation is increasingly used to extract air providing the option to recover the heat energy within the air leaving the building and transfer it to the incoming air via a heat exchanger. This heat exchange can be used in boiler circuits, but increasingly with the installation of heat pumps [9]. The UK Government’s 2050 Pathways Analysis to a low carbon economy includes the specification of technology pathways for the provision of domestic heating in which heat pump technologies contribution to the technology split is as high as 90%; with air source heat pumps contributing 60%; where the fuel dependency is mainly electricity [10]. The delay in the 2011 Renewable Heat Incentive eligibility to include air source heat pumps is inferred to have reduced the incentive for take up notable in the private sector; but with additional Department of Energy and Climate Change (DECC) funding within the UK from the Building Innovation Program and opportunities or EU-match funding has supported take-up specifically for social housing providers [11].

3. Case study

The case study is a residential low carbon development completed in 2010 in Wales, UK; consisting of 13 properties within two-“terraced” blocks [3]. There are houses with two, three and four bedrooms; one first floor maisonette with one bedroom; and eight flats with one bedroom, at ground floor or first floor level [2, 3]. The houses and maisonette are of ‘traditional’ in the UK brick-block cavity exterior wall construction, designed to level three plus of the UK’s Code for Sustainable Homes [CfSH]. Whereas, the flats, are timber-frame and cedar clad with a sheep-wool insulation in the cavity; incorporating triple glazing and photovoltaics, thereby achieving CfSH Level 4. All dwellings are electricity-only with space and water heating provided by NIBE EASHPs with under-floor heating systems with no further cooling provision. The final design air tightness were 2.8 m³/h.m² and 4.8m³/h.m² for the flats and houses respectively. The flats are ‘identical’ one-bedroom single-occupancy with a separate lounge, kitchen and bathroom areas; the floor area of the flat documented in this paper is ≈47.2m² with a living area (lounge) of 14.64m² and a single storey height of 2.4 meters. The brick-block houses are two and three bedroom multiple-occupancies with a typical; kitchen, lounge and shower-room on the ground floor with bedrooms and a bathroom on the first-floor. The house which was monitored in detail to the same extent as the flat documented in this paper is a two-bedroom semi-detached house, has a floor area of 78.10m² and a living area of 12.83m². Photovoltaic panels (PV) were installed at the time of construction on the flats to off-set energy-usages for CfSH-certification, the PV on the houses were installed post-construction and post-occupancy, in 2012. More information on the construction and the floor plans for each of the dwellings and their location is discussed here [3].

Of key importance in undertaking the comparative evaluation at the case study site was the difficulty in tracing full documentation, evidence of the construction, installation and commissioning processes as undertaken by and from the building contractor; whom subsequently declared bankruptcy in 2014. There is a compliance requirement within the statutory UK Building Regulations (at the time of design) for example: Approved Document L1a (2010) “Conserving of fuel and power requires; “…providing the owner with sufficient information about the building, the fixed building services and their maintenance requirements so that the building can be operated in such a manner as to use no more fuel or power as is reasonable in the circumstances” [8]. This prevents verification of necessary key information in the evaluation of the overall Building Performance of the dwellings and development and suggests an oversight by the building contractor and possibly the local government Building Control office.

4. Methodology

The BPE project at this case study builds upon an earlier study, which investigated the performance of exhaust air source heat pumps (EASHPs) in residential properties in Wales, UK [12]. In this former study, it was found that space heating, water heating and the electrical consumption of the EASHP being monitored was very low over one climatic season [ibid], which was contradictory to many UK projects using this technology for space and water heating in 2012
to 2012 [13] [14]. The methodology and findings from this former project informed the funding bid for the UK’s Technology Strategy Board’s BPE programme in 2012, specifically investigating actual monitored energy-usage data with internal and external climatic data, for one heating and one non-heating period, to evaluate the efficiency and effectiveness of the provision of EASHP space and water heating systems within two different building-types and associated occupancy-types. In addition, to a comparative analysis between traditional brick-block construction and timber frame-clad construction, specifically in relation to the final designed and as-built air-tightness, energy-usage, dwelling operational costs and the provision of internal temperature comfort-levels via EASHPs and under-floor heating systems.

This paper documents some of the 12 month monitoring data for energy use, environmental performance and the coefficient of performance (COP) of the EASHPs; from July 2013 to June 2014; which included one heating season. The main reporting for the project completed in December 2015, after several iterations and as such publication of final results was not possible until 2016; however some were published here in 2014 [3] and here in 2015 [15]. The methods used to capture this data included a Davis Advantage Pro2® weather station, recorded at ten minute intervals (extrapolated to five minute intervals, a requirement of the InnovateUK monitoring protocols). CO₂ measurements both internal and external were monitored via Esense-Tr CO₂ transmitters connected to a Digirail 2A Modbus analogue unit, recorded at five minute intervals; see Table 1 below.

Two dwellings were monitored in detail, a single bedroom and ground floor single-storey flat; and a two-storey, two bedroom house; and two other dwellings – one flat and one four bedroom house, to a lesser extent (each property: total energy use, energy use of the EASHP, energy use of the domestic hot water plus space heating). In one dwelling of each build-type within the development, all living spaces’ were monitored for internal environmental temperature (°C), relative humidity (RH%) and external openings (window or door) fenestrate position (0/1) using SpYdaq® sensors. Five minute interval data was recorded via a Modbus base station. Energy-usage circuits; total building energy, total heating energy including hot-water, cooker and shower, power and lighting-circuits; where installed, were monitored per 0.1Kwh usage. The accuracy is ±0.4%, via installed circuit transducers; installed PV-generation system is also monitored. EASH heating energy output in 1.0Kwh units and volume, 0.1m³ usage for; space-heating, hot and cold water were monitored and calculated at five minute intervals, using Kamstrup Multical 420 Flow meters and 402 Heat meters connected to a Modbus Digirail4C data counter with a system accuracy of ±0.4%. Illustrations and the schematic layouts for the monitoring and transmission equipment will be presented at the SEB16 conference, the ten page limit prevented the inclusion of the images within this paper.

5. Results

Results are presented for one of the flats in terms of internal temperatures and the actual performance of the EASHP; commencing with an analysis of the climatic data in the monitoring period.

5.1 External Temperatures

Fig 1. below describes the on-site monitored average, maximum and minimum daily external air temperatures for the monitored period July 2013 to June 2014, where the yearly monitored mean average temperature is 10.86°C within a daily averaged temperature range of 23.10°C to 2.20°C and a maximum-minimum temperature range of 29.30°C to -1.20°C recorded. Monitored weather data is compared with the UK Met-office regional weather data for Wales based

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (ave/high/low)</td>
<td>Centigrade (°C)</td>
<td>0.5°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>Percentage (%)</td>
<td>3-4%</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>metre/second (m/s)</td>
<td>1m/s</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>Degree (°)</td>
<td>3°</td>
</tr>
<tr>
<td>Barometric Pressure</td>
<td>milliBar (mB)</td>
<td>1.0mB</td>
</tr>
<tr>
<td>Rainfall</td>
<td>Millimeter (mm)</td>
<td>0.20-0.25mm</td>
</tr>
<tr>
<td>Global Solar Radiation</td>
<td>Watts/minute² (W/m²)</td>
<td>5% at 1000W/m²</td>
</tr>
</tbody>
</table>
on the rationale that the default building location, i.e. Wales, is also the default climatic regional data used in the 2010 and 2014 Standard Assessment Procedure (SAP) calculations [16]. Compared to the 1981-2010 regional monthly averaged temperature baselines; with the exception of November 2013 where the recorded average monthly temperature -0.6°C below the 1981-2010 average, monthly temperatures during the monitoring period July 2013 and June 2014 were above average; with temperatures >+1.0°C the 1981-2010 baseline in January to April and June. For July and October 2013 the averaged regional monthly temperatures were in excess of +2.0°C of the baseline; in July this coincided with a period of extreme temperatures during a ‘heatwave’ though sunshine-hours of 107% is unexceptional though July was the third sunniest on record. Overall the moderate climate of South Wales, UK is inferred from the installed heating system audit undertaken to have outdoor design temperature of -5°C. For the SAP-heating period of October-through to-May, average temperatures are observed to be constantly below 15.0°C, with average temperatures of <10°C observed to be sustained from end of October (26th) through to mid-March (16th). Minimum average temperatures are observed in November, 2.9°C (18th), and in January of 2.5°C, (29th), with average temperatures of <5.0°C regularly observed between mid-November (18th) through to the end of March (27th).

Fig. 1. Monitored daily average, high and low external temperatures July 2013 to June 2014

External temperatures are compared to a baseline ‘heat demand external temperature’ determined as minus ≈2.5°C of the SAP-derived Adjusted Internal Comfort Temperature [16]. For the SAP-2010 the Adjusted Internal Comfort Temperatures of 19.6°C for the flat averaged baseline external heat demand temperature of 17.25°C is determined. The 2014-SAP Adjusted Internal Comfort Temperature is 21.0°C for both Dwelling-types therefore a baseline heat demand external temperature of 18.5°C is determined. Average temperatures for July 2013 are sustained above both the 2010 and 2014-SAP heating demand temperatures with a maximum of 28.75°C during the heat-wave event. Average external temperatures fall below the 2010 and 2014-SAP heating demand temperatures at the start of September (02nd); with infrequent, <2, and unstained days above the either of the SAP-heat demand temperatures, thereby extending the SAP-heating period. External temperatures at the end of the SAP-heating period, May 2014, are observed to remain below both the 2010 and 2014-SAP heating demand temperatures and into the non-heating period of June 2014 before being maintained above the 2010-SAP and equal to the 2014 heating demand temperature by mid-June (12th) though observed to fall to <15°C on individual days further extending the heat demand period beyond the SAP-period of October to May.
5.2 Internal temperatures – flat

Fig 2 below describes the daily averaged, maximum and minimum recorded temperatures in the living-space (lounge) from July 2013 to June 2014, in the flat case study.

Overheating assessment - Internal temperatures above the Chartered Institute of Building Services Engineers (CIBSE) guidelines [17] for internal overheating; ‘warm’ >25°C within bedrooms and ‘hot’ >28°C within living areas of a dwelling with the threshold determined as >1% occupancy time during any singular event; are observed for July 2013 and June 2014 within both living-lounge and non-living-bedroom areas. A maximum internal temperature greater than 28.22°C is observed in the lounge on the 22nd July only, the average daily temperature remains below the threshold at 26.81°C for the same date. This occurs at the end of the sustained period, (07th-22nd) of high, (>20.0°C) external temperatures. In the non-living space bedroom temperatures greater than the guideline threshold are observed more frequently; for the periods of 13th-17th, 20th-24th and 27th-30th July maximum temperatures greater than 25.0°C with a maximum of 26.73°C observed.

Concomitant with this, temperatures in excess of 25.0°C are observed for the monitored averaged daily temperatures on 21st-23rd with minimum temperatures also in excess of the threshold on the 22nd. Notable the trend is observed in the post-heating month of June with maximum temperatures above 25°C over a prolonged period (12th-27th) with the maximum temperature of 26.88°C recorded on the 23rd. Average daily temperatures exceed 25°C on two occasion 13th-16th and the 21st-25th with minimum temperatures also +25°C on the 23rd-24th. These observations are consistent with the 2014-SAP Regulation Compliance assessment for overheating as being ‘High’ in context of the inadequate ventilation commissioning and contrary to the 2010-SAP “Not Significant” assessment.

Space heating assessment - As highlighted above the actual heating period is observed to extend beyond the SAP-heating period into the preceding September and post June months. Overall, actual monitored internal temperatures for the SAP-heating period (October-May) indicate that the monitored internal living space monthly averaged temperatures remain below the 2014-SAP Adjusted Internal Comfort temperature of 21.00°C for the heating period. November is the only month that the living-space internal temperature falls below the 2010-SAP Adjusted Internal Comfort Temperature of 19.78°C Temperatures in non-living space; i.e. monitored bedroom remain below the 2014-SAP derived non-living space temperature of 19.76°C; being comparable to the 2010-SAP living space temperature; during November-December and February-March. Internal living-space (lounge) temperatures are observed to fall below the 2014 SAP-Adjusted Internal Comfort Temperature of 21.0°C from early October (09th) and only slightly later (15th) for the 2010-SAP bellow 19.6°C. Internal living-space temperatures, average, maximum and minimum, fluctuate above and below both SAP baselines until mid-April (13th) when internal temperatures are observed to
remain above both SAP Internal Comfort Temperatures. For the period 05\textsuperscript{th} January to 07\textsuperscript{th} February living space temperatures are observed to be maintained above the 2010-SAP temperature of 19.78°C but below the 2014-SAP temperature of 21.0°C. Daily averaged temperatures range from a minimum of 19.39°C to a maximum of 21.00°C with a minimum temperature range of between 13.04°C to 20.04°C and maximum temperatures between 19.50°C to 22.20°C. The observed minimum monitored internal temperatures; average, minimum and maximum; occur in October and conversely the maximum monitored temperatures in January. For these months the external temperatures for October (with the exception of a single day) remain >10-<15°C with January temperatures remaining below <5.0°C; notable the monthly monitored space-heating energy outputs are 39Kwh and 325Kwh for October and January. There is also an observed temperature differences between the two living (lounge) and non-living (bedroom) spaces for example; at a minimum external temperatures of -1.2°C the average daily temperatures are 19.60°C lounge and 18.71°C bedroom respectively, with a maximum and minimum range of 20.13-19.05°C and 19.66-17.59°C respectively. Notable, variations between the living and non-living areas are observed indicating that temperature stratification within the dwellings, for differing reasons, are a significant factor. Further, internal heating is observed to respond to passive external gains with increasing average external temperatures with a concomitant time-lag in heat losses within both property-types as external temperatures decrease which is underestimated in the SAP-assessment calculations. These observations for heat energy usage, particularly space heating and the internal temperature outcomes are notably cavedated by the reported inefficiencies of the installed heating systems within all dwellings suggesting that incomplete testing, incorrect commissioning and subsequent inadequate maintenance of the installed NIBE systems it is inferred that the original design intents, which include both the original design intents for space-heat demands and the ventilation requirements can never be met regardless of the reported building fabric and occupancy interventions reported here [15].

To give context to some of the results presented below, results of the monitored energy use versus the SAP predictions for both dwellings monitored in detail from 2010 (calculated by the building contractor) and recalculated by the authors of this paper in 2014 are discussed in more detail here. In addition, discussion about construction fabric weaknesses related to noteworthy differences in the air permeability test results from 2010 (building contractor commissioned) and in 2013 (during the BPE study) and also in-situ U value tests conducted during the BPE study are also discussed here [ibid]

5.2 Coefficient of Performance (CoP) of Installed NIBE EASHP Heating Systems

One of the key objectives of the BPE case study is to provide information and data to further evaluate the perceived high energy usage, concomitant CO\textsubscript{2} emissions and associated running costs with the provision of space and water heating from EASHPs in the UK, particularly with underfloor heating systems. As reported above the internal temperatures for the heating period, October-to-May 2013 are only intermittently maintained. From the audit of installed building heating services there are two key factors which are impacting the evaluation of the overall Building Performance of the monitored dwellings, incorrect commissioning and maintenance of the installed NIBE EASHP systems, and inappropriate occupant interfacing with both the installed technology (including underfloor heating) as well as the heating system controls. The NIBE F205P, an EASHP is designed for heating demands of 2-4Kw, NIBE published data includes a COP 3.15, according to EN 14511, A20(12)/W45 at 100m\textsuperscript{3}/hr ventilation flow rate and COP of 4.27, according to EN 14511, A20(12)/W35 at 200m\textsuperscript{3}/hr ventilation flow rate [18]. The Derived CoP weekly values from monitored data for the flat is given in Fig 3 below. Derived CoPs were determined from the monitored [Total Heat output (Kwh)] divided by the [Total Heat (Space and Hot Water) Electricity usage (Kwh)]. The derived CoP/efficiency includes the electricity usage of the immersion heating provision and the ancillary fans, pump and ‘stay-hot’ as well as the electricity consumed by the heat pump. The rationale not to exclude the immersion and ancillary usages is based on the improper use of the heating control systems by the occupants such that there is evidence of an over-reliance during the monitored heat-demand period on either; the heat recovery system as the main heat input and/or the automatic immersion heating system. Adjustment of the monitored data, for example using the SAP calculated sub-circuit demands, provides incongruous electricity usage data outcomes. The pattern of trends in usage, output and CoP values are discussed in context of the highlighted technical issues above.

By plotting the Total Heat Electricity usage and the Total Heat output against the Derived CoP; the extrapolated Kwh values for each variable at the NIBE published CoP values, given above for each system, is derived. Using the above calculation an estimate of the ACTUAL maximum CoP/efficiency value for the heating systems as currently
commissioned and used by the occupants is derived and compared against the NIBE CoP in context of the impacts of the technical issues as highlighted above. Derived CoP values and the overall general trend of Total Electricity usage and Total Heat outputs are deemed to be typical of increasing and subsequent decreasing heat outputs across the heat demand months of October 2013 to May 2014. A comparison with the published NIBE CoP value is given in Table 2 below.

![Graph: Weekly Derived Heating System CoP for Flat](image)

Fig. 3. Weekly Derived Heating System CoP for Flat

<table>
<thead>
<tr>
<th>NIBE SYSTEM</th>
<th>NIBE-Published CoP</th>
<th>Derived CoP Maximum (Difference)</th>
<th>Derived CoP Minimum (Difference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fighter 205/Flat TF/C-F1</td>
<td>3.15</td>
<td>1.733 (-1.417)</td>
<td>0.370 (-2.78)</td>
</tr>
</tbody>
</table>

The above analysis of Derived CoP and the significant differences from the published NIBE CoPs for the system installed at the case study, these are caveated in context of the reported conclusion to the installed system audit; “Therefore this (installed systems) review has been unsuccessful in determining if, a) if the installations meet the design requirements, or b) if the commissioning had been carried out to meet design intent. These are key failings of the delivery process and the consequences will be detrimental to the long-term, successful performance of these dwellings”. Extrapolation of monitored Total Heat Electricity usage and the Total Heat output to the published NIBE CoP values indicates that the current efficiency performance of the installed heating and ventilation systems means that, regardless of other external factors, the systems cannot operate to the manufacture’s efficiencies as summarized in Tables 3 below.

6. Discussion

The case study presented in this paper highlights discrepancies between ‘As designed-As built’ and the ‘As-built Post-occupancy In-use’ performance of low carbon housing as to potentially undermine the UK’s zero carbon housing policy 2050 targets. The discrepancies identified are multi-facetted including foremost performance of the component elements and construction of the building envelope and the installation, commissioning and subsequent maintenance of installed heating EASHP systems. Identified building fabric issues including: component design discrepancies, thermal bridging and air tightness that significantly reduce the thermal performance within both Build-types are inherited from the final construction process as at the time of completion; discussed here [3, 15]. Whilst, the results described and discussed here are caveated by the acknowledgement that external factors including, building settlement and occupier usage will have an immeasurable impact on the observed issues; these factors are inferred to be negligible.
in comparison to the indicative deficiencies in the realisation of the stated Construction Details in the delivery of the finalised design components of the dwellings building fabric.

Table 3. Comparison of NIBE published CoP with Derived CoP from monitored data for Flat

<table>
<thead>
<tr>
<th>Value/Variable</th>
<th>Flat</th>
</tr>
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<tbody>
<tr>
<td>NIBE published CoP</td>
<td>3.15</td>
</tr>
<tr>
<td>Extrapolated monitored Total Electricity Usage (Kwh) at NIBE CoP 3.15 value</td>
<td>80.0</td>
</tr>
<tr>
<td>Extrapolated monitored Total Heat Output (Kwh) at NIBE CoP 3.15 value</td>
<td>162.5</td>
</tr>
<tr>
<td>Maximum derived CoP from extrapolated monitored data (Maximum CoP for heating systems as monitored (As-Built post-occupancy in-use))</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Incorrect testing and commissioning of the installed heating and ventilation systems means that, regardless of other external factors, the installed EASH P-systems cannot operate to the manufacture’s efficiencies and therefore no conclusions can be drawn of the effectiveness of the installed technologies in reducing energy consumption, associated emissions and operating costs. Importantly, the outcomes of this project highlight noteworthy issues surrounding the use of newer technologies to meet increasingly stringent energy and emission efficiency demands without the necessary knowledge and understanding within all stakeholders in the delivery of the theoretical design requirements in reality. Further, this is translated ‘down-the-line’ in the life-cycle of the dwellings such that the installed systems, which will degrade with use and age are maintained correctly to be operating to the potential maximum efficiencies. This not only has efficiency benefits for the end-users but is inferred to be a long-term ‘more cost-effective’ approach for the actual owners. Analysis also highlights the existence of a ‘knowledge gap’ within the end-users such that the occupants have developed behavior strategies in the provision of their internal comfort levels and environmental conditions using the installed heating and ventilation. Certain actions have a significant detrimental effect which further exasperate the effectiveness of the installed systems and are also reflective of the barrier between users and new technologies in that there ‘appears’ to be evidence that older technologies; central heating and extractor fans for example, provide a greater feeling of control of the end-user internal environments. In conclusion the observed ‘Performance Gap’ in the monitored dwelling can be best described as a ‘Knowledge Gap’ in the overall processes of Design –through- Construction-Commissioning and Hand-Over’ –to- the final End-users. Well-intended design intents which ‘on-paper’ meet the legislative-drivers for dwellings impose significant challenges during the construction and commissioning of the buildings and the increasing use of ‘newer’ technologies actually barriers to the end-users such that the original design intents can never be fully realized. This would appear to be pertinent in dwellings built for social housing where there is the significant issue of ‘personal’ investment in the dwellings between the owner and their tenants [ibid]. The results presented in this paper and also documented in the executive report [19] and the final report [20] for the Welsh low carbon micro-community could contribute to the creation of an independently-funded heat pump system performance test facility and the publicly-available results database, as recommended by Irving [21] in 2013. As part of his PhD Irving [ibid] undertook an assessment of the potential of heat pumps to reduce energy-related carbon emissions from UK housing in a changing climate.

7. Acknowledgements

The authors give their thanks to the Housing Association partner in this project, to the InnovateUK for co-funding the BPE project for the case study; and the tenants in the dwellings where the monitoring equipment was installed.

8. Conclusion

This paper has discussed the monitoring findings from a BPE study, which was completed in 2015, on a low carbon micro community in south Wales, UK. In particular the results presented are those illustrating the external temperature
versus internal temperatures in one of the dwellings. In addition, the CoP of the installed EASHPs is also discussed and found to be considerable lower than manufacturer’s guidelines. The paper illustrates the inadequacy of the installed systems to maintain internal temperature within minimum comfort ranges for some months of the monitoring period, but caveats that due to incorrect installation, commissioning, operation and maintenance of the EASHP it is difficult to conclude that these systems are inadequate for the UK.

9. References