Performance monitoring of energy efficient retrofits – 4 case study properties in Northern Ireland

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Performance monitoring of energy efficient retrofits – 4 case study properties in Northern Ireland

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Abstract. Approximately half of the houses in Northern Ireland were built before any form of minimum thermal specification (U-value) or energy efficiency standard were available. At present, 44% of households are categorised as being in fuel poverty; spending more than 10% of the household income to heat the house to an acceptable level. This paper presents the results from long term performance monitoring of 4 case study houses that have undergone retrofits to improve energy efficiency in Northern Ireland. There is some uncertainty associated with some of the marketed retrofit measures in terms of their effectiveness in reducing energy usage and their potential to cause detrimental impacts on the internal environment of a house. Using wireless sensor technology internal conditions such as temperature and humidity were measured alongside gas and electricity usage for a year. External weather conditions were also monitored. The paper considers the effectiveness of the different retrofit measures implemented based on the long term data monitoring and short term building performance evaluation tests that were completed.

1. Introduction

The UK Climate Change Act 2008 is legislation that enacts a long term legal framework, requiring a reduction of 80% by 2050 on 1990 levels of greenhouse gas emissions. As domestic buildings in the UK are the source of approximately a quarter of all CO_2 emissions, significant reductions will be required to achieve this ambitious target. According to the most recent Northern Ireland Housing Condition Survey there are 760,000 dwellings with a poor average energy efficiency SAP rating of D. Housing in Northern Ireland is old and inefficient with approximately 50% of houses built before the first minimum building thermal performance standards, introduced in1973 (Northern Ireland Housing Executive, 2013). Whilst the energy efficiency of some dwellings may be easy to improve using relatively non invasive measures such as cavity wall insulation, loft insulation and double glazing other dwellings are categorised as "hard-to-treat". Solid wall houses are categorised as "hard-to-treat" with cost effective energy efficiency improvements often difficult to implement [2]. Across the UK there are approximately 6.5 million solid wall houses. The typical construction of these pre-1919 houses is single leaf solid red brick 225mm thick with a constructed U-value of 2.0 W/m^2K. There are 87,600 solid wall houses in Northern Ireland, of which 95.3% have a SAP score lower than C. The two lowest possible bands of F and G represent 37.3% of all pre-1919 houses. To ensure we achieve the ambitious 2050 target, effective methods to improve the energy performance of such houses will be essential.

Another significant driver to improve the energy efficiency of domestic buildings in Northern Ireland is the issue of fuel poverty. A household is defined as being fuel poor if it needs to spend more than 10% of its income to heat the house adequately. The significant difference in fuel poverty levels in Northern Ireland compared to other regions, as shown in Table 1, is attributed to a number of factors including lower income, higher fuel prices and larger dependency on electric, solid fuel and oil [1]. The rate of fuel poverty in Northern Ireland is amongst the worst in Northern Europe and 1,890 excess winter deaths over the last decade have been directly attributable to people living in damp and cold homes [3].

Table 1. Fuel poverty rates across UK regions

Country	Households in fuel poverty (%)
Northern Ireland	42
England	16
Scotland	28
Wales	29

This paper presents results of four solid wall homes based in Northern Ireland of which three have had significant energy efficient measures implemented. The fourth case study has undergone some conventional upgrades to the building fabric that would be typical for Northern Ireland. To understand the effects of the retrofit measures implemented long term performance monitoring of the internal conditions and energy consumption for space heating and electricity were measured.

2. Case study properties

The properties are owned by a Social Housing provider, an organisation that provides housing to those on lower incomes. The houses are in close proximity to each other and are set in an urban environment.

2.1. Building fabric

In house 1, 2 and 3 the walls were internally insulated using a number of different materials as outlined below:

- House 1 - 100mm sheep wool, 50mm polyisocyanurate board and 6mm magnesium board.
- House 2 – 20mm aerogel board and 9mm magnesium board
- House 3 – 60mm wood fibre insulation board and 9mm magnesium board

In an effort to reduce thermal bridging at the junction of the internal insulation and the 1st floor level 300m of sheep wool insulation was added next to the external wall in each house. In the roof space of house 1, 2, and 3, 200mm glass mineral wool insulation was laid down between floor joists. The underside of the roof space had 30mm PIR insulation and 6mm magnesium board fixed to the underside of the ceiling joists. In the roof space 200mm of glass mineral wool insulation was added in houses 1,2 and 3. Argon filled double glazing has been fitted in timber sash windows in house 1,2 & 3. New insulated solid floors with expanded polystyrene insulation and concrete screed were added too all of the case study houses. House 4, which has undergone minimal retrofit, has a10mm plasterboard fixed to 21mm expanded polystyrene board and vapour barrier. The windows in house 4 are timber framed single glazed sash windows.

2.2. Air permeability

Ventilation was provided in house 1, 2 and 3 through a Mechanical Ventilation and Heat Recovery (MVHR) unit with an efficiency 78.2%. Open fire places and chimneys in house 1,2 and 3 were sealed up and replaced with gas fires whereas the chimney in the living room of house 4 remains open. A number of diagnostic tests where completed on each property including air-tightness tests to the BS EN 13829-2001 standard. All vents and extract fans were temporarily sealed and drains filled with water. The results of the air-tightness tests are presented in last line of Table 2. UK building regulations stipulate that new homes should have a maximum design air permeability of 10m^3/hr.m^2 under a pressure of 50Pa. There is no such design value for retrofits to houses. The four case studies all exceed this recommended air-tightness design value for new builds. As expected House 4 which has not undergone significant retrofit measures has the worst air-tightness value. This higher air permeability is likely to be caused in part by the open chimney in the living room. Difficulties with achieving air-tightness in energy efficient retrofits are well documented. A study of 102 retrofit properties [4] has shown large variability in the air-tightness. Trends in age or wall type and air-tightness were not established. Pre-retrofit air-tightness results were between 2-23 m^3/hr.m^2 and post-retrofit 2-15 m^3/hr.m^2 however some air-tightness results were marginally worsened with the report concluding that air-tightness measures need to be integrated better with other upgrades such as installation of floor/wall insulation or MVHR system.

According to [5] to make the most efficient use of any installed MVHR system the design air permeability should be between 2 – 4 m^3/hr.m^2 . Given the high air permeability of the case study houses 1, 2 and 3 it is likely that the MVHR will not be performing efficiently and may not even be required.

2.3. Space heating & domestic hot water systems

The space heating system and domestic hot water in houses 1, 2 and 3 was provided by a condensing gas boiler with a seasonal efficiency 89.5% with heat distributed through an underfloor heating system on the ground floor and radiator system on the first floor. Space heating and domestic hot water in house 4 was also provided by a condensing gas boiler with a seasonal efficiency of 89.2% and distributed through a radiator system.

Table 2. Summary of case study houses

	House 1	**House 2**	**House 3**	**House 4**
Wall U-value	0.22 W/m^{2}K	0.52 W/m^{2}K	0.45 W/m^{2}K	0.93 W/m^{2}K
Floor U-value	0.22	0.22	0.22	0.41
Roof U-value	0.16	0.16	0.16	2.07
Door U-value	2.2	2.2	3.0	3.0
Window U-value	3.10	3.10	3.10	5.4
Floor area (m^2)	102.85	62	58.2	56.55
Occupants	2 adults	2 adults & 1 baby	2 adults	1 adult
Occupancy hours	24 hour	Shift worker – occupancy pattern changes	Both shift workers	Occupant works part-time 11am-3pm
House type	Terraced	Terraced	Detached	Terraced
Air-tightness m^3/hr.m^2 at 50 Pa	15.04	14.14	10.52	17.21

2.4. Building performance evaluation

Temperature and humidity was measured at three locations in each of the properties; living room, bedroom and bathroom. Total gas and electricity consumption within the properties was also metered. The results of a yearlong monitoring period between the 1st August 2014 and 31st July 2015 are presented in this paper. As with any long term monitoring project a number of difficulties were encountered with data gathering due to a range of technical difficulties. Data was gathered using wireless sensors which sent data back to a central unit which transmitted the information to the cloud. In particular, gas data for house 2 and 4 was lost when the monitoring device failed. In these cases data gathered from site visits, discussions with tenants and typical consumption patterns were used to estimate gas usage.

2.5. Relative humidity in case study houses

Relative humidity in range of 40 to 70% is considered acceptable for a comfortable environment[6]. If humidity levels exceed 70% over long periods in a room the potential for the development of house dust mites, airborne fungi, mould and bacteria is increased. Mould growth is likely on surfaces if humidity levels are over 80% for than 6 hours of the day. These growths in turn emit spores, cells, fragments and volatile organic compounds. Chemical and biological degradation of materials is also initiated by dampness, which further pollute internal air. Dampness is considered to be a strong and consistent risk indicator for the development of asthma, respiratory infections such as bronchitis and allergies [7]. Humidity levels may fall below 40%, particularly during spells of sustained cold weather, however associated risks appear minimal with an increased chance of static electric shocks for occupants [6]. A summary of the measured relative humidity in the living room and bedroom of each property is presented in Table 3.

Table 3. Annual relative humidity in bedroom (BR) and living room (LR) of case study properties

	House 1		**House 2**		**House 3**		**House 4**	
Relative humidity (% hours in range in 1 year period)	BR	LR	BR	LR	BR	LR	BR	LR
≤40%	28.9	0.7	24.1	31.8	7	9.1	6.4	50.5
40%-70%	71.1	99.0	75.9	68.2	93	90.9	93.6	49.5
≥70%	0	0.3	0	0	0	0	0	0
Average winter relative humidity (%)	29.3	36.1	42	36	45.7	44.7	47.2	41.3
Average summer relative humidity (%)	36.3	43	42	47.5	45.6	43.2	50.9	38.4

None of the case study properties have sustained levels of high relative humidity and for the most part fall within the limits of CIBSE recommendations. House 3 has the highest percentage of time of hours in the 40% to 70% humidity range. This could possibly be linked to its relatively low air permeability value.

2.6. Internal temperature in case study houses

Internal temperatures between 17˚C and 25˚C are considered to be comfortable and are recommended by CIBSE[6]. Prolonged exposure to low temperatures in houses have been linked with lowered resistance to infections with temperatures below 16˚C being associated with respiratory issues and cardiovascular problems at temperatures below 12˚C [8] with the young children and elderly people most vulnerable. CIBSE also recommend summertime peak temperature and overheating criteria of less than 1% annual occupied hours in the bedroom and living room of 26˚C and 28˚C respectively. A summary of the measured temperature over the year-long monitoring period in the living room and bedroom of each property is presented in Table 4.

Table 4. Annual temperature in bedroom (BR) and living room (LR) of case study properties

	House 1		**House 2**		**House 3**		**House 4**	
Temperature %hours in 1 year period	BR	LR	BR	LR	BR	LR	BR	LR
≤17˚C	9.8	0.7	12.6	0	12.9	30	40.4	43.1
18˚C-25˚C	89.3	98.9	87.4	100	87.0	70	59.6	56.9
≥26˚C	0.9	0.4	0	0	0.2	0	0	0
Average winter temperature	21.1	19.3	17.6	20.5	19.0	16.4	14.3	14.2
Average summer temperature	21.9	21.8	21.2	21.6	20.9	17.6	20.1	19.2
% change of winter to summer temperature	3.8	13.0	20.5	5.4	10.0	7.3	40.6	35.2

The low internal temperatures of house 4 are particularly concerning with the living room having temperatures below 17˚C for 43.1% of the time, with temperatures below 12˚C for 8.3% of the time monitored. Temperatures increase from the winter to summer temperatures as would be expected with a changing ambient temperature. House 4 also sees the largest seasonal variation with bedroom and living room temperature increasing 5.8˚C and 5˚C from winter to summer respectively. The bedroom temperature in house 2 also has a significant change with a 20% increase in temperature; however this may be explained in part by the arrival of a new baby around that time period. The average living room temperature is also marginally below recommended temperatures.

The rate and pattern of heat loss associated with house 4 is markedly different from the other case study houses as shown in Figure 1. Over a period of a week in the month of January the living room temperature of House 4 has a steep, almost exponential, decline of heat daily. The temperature decline in other case studies whilst having a similar cyclical pattern of decreasing temperature at night are significantly less pronounced. Using the CIBSE criteria overheating is not an issue in any case study.

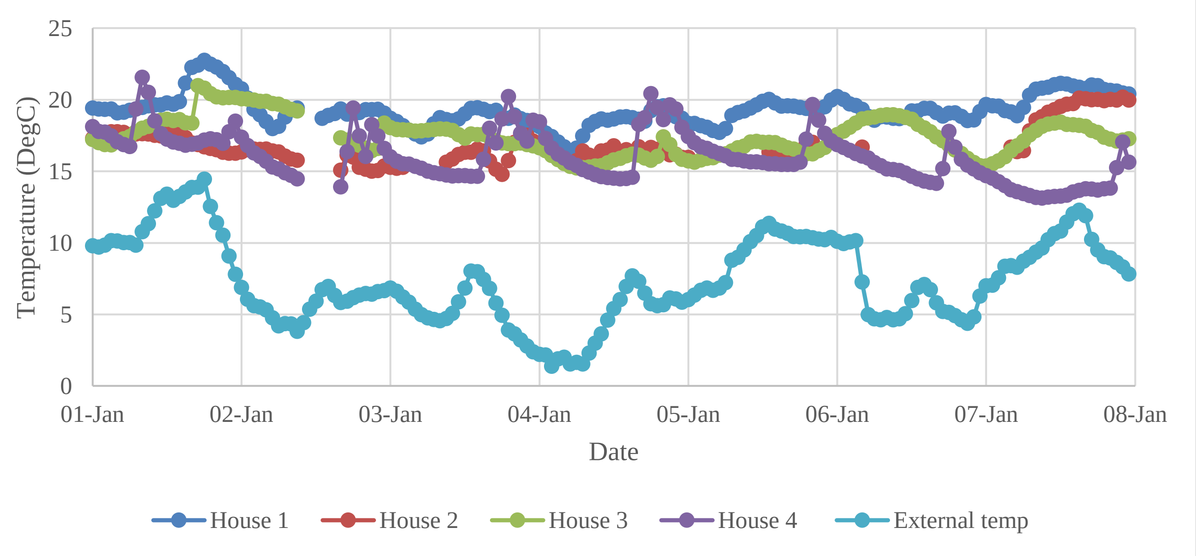

Figure 1. Hourly temperature profile of living room temperature of case study properties and external temperature

2.7. Gas consumption in case study houses

The UK regulator for gas and electricity markets OFGEM [9] has published typical domestic annual consumption values for gas. Users are categorised as "low", "medium" or "high" consuming 8,000 kWh, 12,500 kWh and 18,000 kWh respectively. Given the wide variety of age and type there is a lot of complexity associated with improving energy efficiency of existing houses. The "performance gap" between design and actual values also means it is difficult to benchmark energy use in domestic retrofits. The Low Energy Building Database has compiled information on 33 UK domestic refurbishments and lists a range of actual primary energy use of 37.5 kWh/m^2/yr to 283 kWh/m^2/yr. This large range makes it difficult to establish what a realistic and achievable standard in retrofitting houses is. For new builds in the UK the Fabric Energy Efficiency Standard (FEES) have set good practice maximum space heating energy demand to be 39kWh/m^2/year for apartments and mid-terrace houses and 46kWh/m^2/year for end of terrace, semi-detached and detached houses [10]. This standard has been created to allow for the efficient implementation of zero carbon or low carbon technologies in new domestic buildings and is therefore ambitious in the context of retrofitting properties. A summary of actual gas consumption and these benchmarks are presented in Table 5.

Table 5. Annual gas consumption for case study houses compared with benchmarks

	House 1	**House 2**	**House 3**	**House 4**
Gas consumption (kWh)	17724	7753[1]	8514.7	5382[2]
OFGEM User Category based on actual gas consumption	Medium	Low	Medium	Low
FEES best practice (kWh)	4011	2418	2677	2205

[1] gas monitoring for this property was interrupted from the 28th October until the 16th December – a conservative estimate for usage based on typical gas consumption for the property is presented.

[2] gas monitoring for this property was interrupted from the 20th Jan until the 1st of May – a conservative estimate for usage based on typical gas consumption for the property is presented.

As expected gas usage in each of the four properties far exceed best practice FEES standard. Even though extensive retrofit measures were implemented in house 1, 2 and 3 the effectiveness of these measures at reducing energy usage in the households is questionable. House 4 has exceptionally low gas consumption which when twinned with the consistently low internal temperatures is likely to signify that the occupant in this property is unable to afford to heat the house sufficiently and could be classified as being in fuel poverty.

2.8. Electricity usage in case study houses

To evaluate the actual electricity usage of the four houses a number of literature sources were used to establish typical or predicted electricity consumption patterns with results summarised in Table 6. The most recently published figures for typical annual electricity consumption from OFGEM [9], have been categorised as "low", "medium" and "high" users who consume 2000kWh, 3100kWh and 4600kWh respectively. The report presents the findings of a survey of electrical energy consumption in 251 households. The average electricity consumption in households without electric heating was found to be 3638 kWh/year which when expressed in terms of house floor area resulted in 65kWh/m^2/year. A study of 27 households in Northern Ireland [11] found that electricity consumption had a strong relationship with the floor area of the building with the following correlation equation presented - 49(Area m^2) + 233 = electrical kWh consumption.

The actual electricity consumption of the four house is presented alongside the predicted annual electricity consumption based on the previous literature (Zimmermann et al. 2012) and (Yohanis et al. 2008) as well as being grouped into a suitable OFGEM category in Table 6.

Table 6. Annual electricity consumption - Actual, predicted and % difference

	House 1	House 2	House 3	House 4
Actual	3094	3798[1]	3056	1871
OFGEM User Category	Medium	Low	Low	Low
Predicted [12]	6685	4030	3783	3675
% difference	116	6	23.8	96.5
Predicted [11]	5272	3271	3084.8	3003
% difference	70	-14	1	61

[1] Data could not be gathered for August until December – the number presented is an estimate based on 6 months of data between January and June of 2015.

House 1 has the largest difference between actual and predicted electricity consumption. Given that the house is under occupied with only two adults present (one of whom is elderly and infirmed, spending significant time in bed) this is not surprising. House 4 has the lowest electrical consumption, despite the occupant using electrical radiators to boost heat in the living room. This low electricity use could be associated with low levels of occupancy and also an inability to afford to pay for electricity.

Figure 2 shows the average daily load profile over the monitoring period of electricity usage in the four houses is compared with an average UK load profile available from a report completed for the Energy Saving Trust (Zimmermann et al. 2012). The daily profile for house 2 and 3 appear to have relatively high electricity demand at night – both houses are occupied by shift workers which would explain this increased overnight demand.

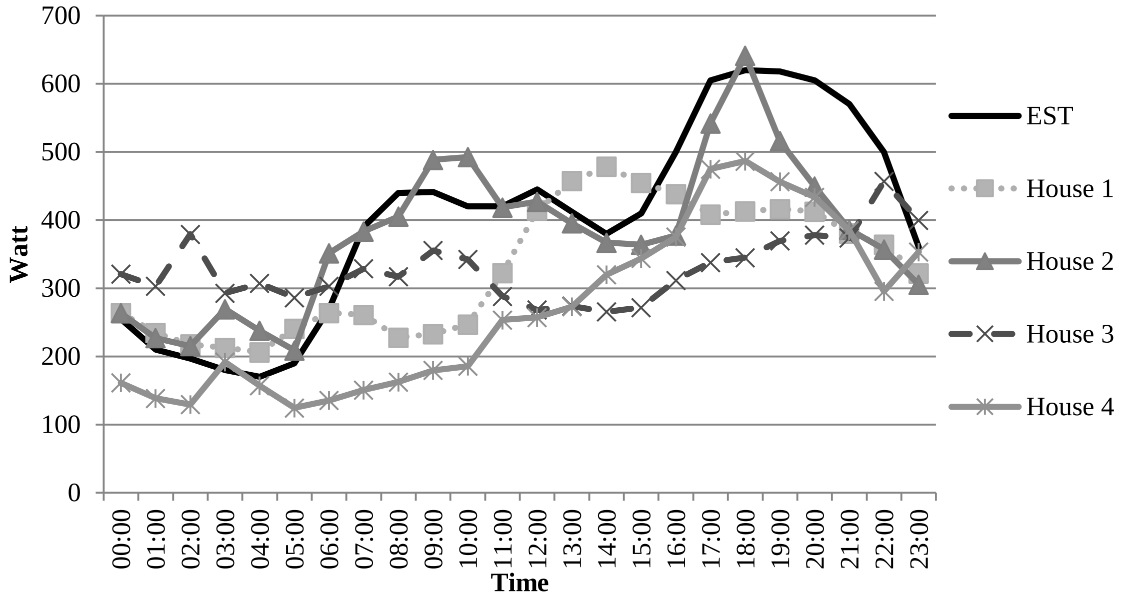

Figure 2. Average electricity profile of case study properties compared to typical UK profile

3. Discussion and conclusions

The prolonged low internal temperature, high relative humidity and accelerated decline of internal temperature in house 4 overnight indicate, as would be expected, that it is the poorest performing property. The low internal temperatures and low gas usage would indicate that the householder is in fuel poverty and is unable to afford heating the house to a sufficient level. The relatively slow decline of overnight temperature from the other case study properties comparatively to house 4 indicate that retrofit measures have been effective at improving the building fabric. Gas consumption for houses 2 and 3 are categorised as low [9], and twinned with generally good internal temperature ranges indicate that the retrofit measures implemented have improved the energy performance and comfort levels of the building. House 1 has the highest internal temperatures of any of the case studies coinciding with the highest gas usage. As one occupant is infirmed and the other is the care giver the priority is warm comfortable internal temperatures which they can achieve whilst still falling within the medium energy user category [9].

Whilst there are a number of sources of typical electricity consumption for households in the UK, there is less comprehensive data available that accurately predicts space heating consumption. Whilst large variations of space heating across homes is understandable due to a large range of variables (occupant preference, age/type/construction of building etc.) transparent benchmarks would be highly beneficial. To ensure we close the "performance gap" between design and actual energy usage we need more rigorous ways of estimating energy use in buildings.

The monitoring of these four case study properties is ongoing with further work planned considering dynamic modelling of energy usage in the buildings. Further work is required to consider the life cycle costing and environmental impact of the measures implemented to understand the financial and environmental benefit of such retrofit improvements.

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