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Building performance evaluation of domestic energy efficient retrofits in current and future climates

McGrath, T.E.[1], Campbell, N. [1], Nanukuttan, S.V. [1], Soban, D[2], Basheer, P.A.M. [3]
[1]School of Planning, Architecture & Civil Engineering, Queen's University Belfast, BT9 5AG, Northern Ireland
[2]School of Mechanical & Aerospace Engineering, Queen's University Belfast, BT9 5AG, Northern Ireland
[3]School of Civil Engineering, University of Leeds, England, LS2 9JT, UK
email: tmcgrath03@qub.ac.uk

ABSTRACT: Approximately half of the houses in Northern Ireland were built before any form of minimum thermal specification or energy efficiency standard was enforced. Furthermore, 44% of households are categorised as being in fuel poverty; spending more than 10% of the household income to heat the house to bring it to an acceptable level of thermal comfort. To bring existing housing stock up to an acceptable standard, retrofitting for improving the energy efficiency is essential and it is also necessary to study the effectiveness of such improvements in future climate scenarios. This paper presents the results from a year-long performance monitoring of two houses that have undergone retrofits to improve energy efficiency. Using wireless sensor technology internal temperature, humidity, external weather, household gas and electricity usage were monitored for a year. Simulations using IES-VE dynamic building modelling software were calibrated using the monitoring data to ASHARE Guideline 14 standards. The energy performance and the internal environment of the houses were then assessed for current and future climate scenarios and the results show that there is a need for a holistic balanced strategy for retrofitting.

KEY WORDS: Building performance evaluation, energy efficiency, climate change, retrofit.

1 INTRODUCTION

The UK Climate Change Act (2008) requires an 80% reduction of greenhouse gas emissions on 1990 levels by 2050 [1]. Approximately a quarter of carbon emissions come from domestic buildings [2]. The Standard Assessment Procedure (SAP) is the UK methodology for rating domestic energy efficiency. Domestic buildings in Northern Ireland are considered inefficient with an average SAP rating of D [3]. Approximately half of the stock was built before any minimum thermal standard, enforced in 1973 [4]. To achieve the ambitious reduction target significant measures to improve the energy efficiency and achieve an average SAP rating of B will be required [2]. Housing stock turnover is low with estimates that between 60-80% of the stock in 2050 is already standing today [5]. Whilst the energy efficiency of some of the stock can be improved with relatively non-invasive measures such as cavity fill, loft insulation and window upgrades some properties are categorised as "hard-to-treat", where cost effective energy improvement measures are more difficult. There are 6.5 million solid wall houses in the UK, single skinned 215mm thick red brick construction with U-value of 2.0 W/m^2K, which are categorised as "hard-to-treat"[6]. There are 87,600 pre-1919 houses of which 95.3% have SAP rating lower than C in Northern Ireland. Of domestic buildings that fall within the lowest SAP bands of F and G, pre-1919 properties represent 52.1% [3].

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 rate of fuel poverty in Northern Ireland is amongst the worst in Northern Europe with 42% of households classed as being fuel poor [3]. There have been 1,890 excess winter deaths over the last decade have been directly attributable to people living in damp and cold homes [7]. In pre-1919 properties 68.7% of occupants are classified as being fuel power, the highest rate for all dwelling age brackets [3].

Given the significant legislative and social drivers the improvement of building energy performance via retrofitting of insulation materials and the inclusion of more efficient heating systems is unavoidable. This change is being lead primarily by the social housing sector who have a responsibility to provide affordable housing.

Due to the predicted changes in global weather patterns the sensitivity of retrofit measures to future climate conditions needs to be considered. Global average temperatures are predicted to rise between 1 to 5°C by 2100. Climate change will result in an increased frequency of extreme weather events with heatwaves and drought during summer months and warmer and wetter winter months. Current retrofit measures are designed considering past weather patterns and the hierarchy of reducing energy focuses on the minimisation of winter space heating. As a consequence of a warming climate there will be additional pressures on the built environment with over-heating and increased need for the use mechanical cooling in domestic housing becoming a possibility [8]. By computer simulation of building performance within future climate scenarios potential issues such as overheating can be identified early, as discussed by [9], [10]. The need for active ventilation systems can be considered as well as gained a deeper understanding of the full building life cycle performance. Generally as energy efficient retrofit measures often prioritise the reduction of winter time space heating there is the potential to exacerbate summer overheating issues in the future. It is important to design any retrofit measures considering the implications of a changing climate.

2 CASE STUDY PROPERTIES

2.1 Retrofit actions taken

The case study properties are owned by a social housing landlord in Belfast, Northern Ireland. The terraced houses were built between 1901 and 1908 and both are solid wall redbrick construction. They are located within a designated special area of conservation zone and alterations to the external façade are restricted. They have undergone significant retrofit measures to improve energy efficiency. House 1 consists of two terraced houses which have been joined together to make a large house suitable for a modern family. It has also had a small extension added to the rear of the property in the 1970s. In 2010, internal wall insulation was applied: 100mm sheep wool, 50mm polyisocyanurate board and 6mm magnesium board. House 2 is a detached property and had 60mm wood fibre insulation board and 9mm magnesium board applied internally, also in 2010. 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 both properties, 200mm of glass mineral wool insulation was laid down between floor joists. The underside of the roof space had a further 30mm PIR insulation and 6mm magnesium board fixed in to the underside of the ceiling joists. Argon filled double glazing has been fitted in timber sash windows. Suspended timber floors were replaced with insulated solid floors with expanded polystyrene insulation and concrete screed.

Domestic hot water and space heating is provided by Worcester Greenstar 30 CDi gas condensing boilers with a SEDBUK certified efficiency of 89.8% [11]. To reduce infiltration, open fire places were sealed in both properties and efforts made to improve air-tightness. Mechanical ventilation heat recovery units were also installed to ensure good air quality using a Brookvent Aircycle system with a heat recovery efficiency of 78.2% [11].

A number of short term performance tests were carried out including air pressurisation tests, thermal imaging surveys and smoke pen tests. Air-tightness test results found that the despite the retrofit measures the building envelope was not effectively sealed as results fall outside current minimum building regulation standards of 10 $m^3/hr.m^2$.

3 MONITORING OF CASE STUDY PROPERTIES

Monitoring data for a year period between 1st August 2014 and 31st July 2015 are presented in this paper. Temperature and relative humidity measurements were gathered in three locations in each property; living room, bedroom and bathroom. Measurements were taken at five minute intervals with battery powered units using a TMP36 temperature sensor and HIH5030 humidity sensor. Gas was measured via a Metrix UG-G4 submeter with pulse outputs at 0.01m^3 intervals. Electricity consumption was measured using a newly developed circuit monitor which sampled both voltage and current wave forms over approximately 2% accuracy in trials completed. Domestic hot water was measured with an ACWA meter with a pulse generated at 1 litre intervals. Data was communicated via a digital mesh network with the information gathered in a powered central unit. Information was then transmitted via broadband connection to the cloud. During the monitoring period over 2 million readings were recorded across the case study properties.

3.1 Internal conditions – temperature and relative humidity measurements

Relative humidity levels between 40 and 70% are considered good as prolonged periods exceeding 70% will increase the potential for the development of dust mites, airborne fungi and bacteria as well as initiating chemical and biological degradation of building materials [12]. The monthly averages show consistent and low relative humidity over the monitoring period. In both properties the relative humidity never exceeded 70% in the living room or bedroom and only exceeded the guideline limit 0.4% and 0.8% of the time in the bathroom in House 1 and 2, respectively.

For thermal comfort, CIBSE recommends internal temperature range of 17-25ºC [12]. Prolonged exposure to low temperatures is linked to a detrimental impact on the health of occupants, respiratory issues at temperatures below 16ºC and cardiovascular issues at temperatures below 12ºC [13]. During the monitoring period in House 1 the bedroom was recorded at below 17ºC for 2.9% of the time whilst the living room was below 17ºC for 1% of the time. In House 2 the bedroom was below 17 for 13.6% of the time and the living room for 38.3% of the time. CIBSE also provide overheating criterion, bedrooms and living rooms should not exceed 26ºC and 28ºC respectively for more than 1% of occupied time. The CIBSE criteria, whilst sometimes criticised for overly simplifying the complex relationship between temperature and thermal comfort [14], are considered an indicative datum for assessing potential over heating issues in properties. Overheating has the largest impact on vulnerable occupiers, elderly and young children, with the UK 2003 summer heat wave associated with 2,000 additional deaths [15]. Bedroom temperatures above the guideline were recorded for 0.4% and 0.2% of time in House 1 and House 2 respectively. Living room temperatures did not exceed the CIBSE limits during the monitoring period in either property. Average monthly temperature and relative humidity measurements for the living room case study properties are shown in Table 1.

Table 1. Monthly average temperature and relative humidity.

	House 1 Living Room		House 2 Living Room	
	Temp (Deg˚C)	RH (%)	Temp (Deg˚C)	RH (%)
Aug-14	22.4	39.8	19.4	49.0
Sept-14	21.9	41.8	20.6	49.8
Oct-14	21.1	39.6	18.3	53.5
Nov-14	20.6	37.2	19.6	51.7
Dec-14	19.6	31.6	18.3	47.2
Jan-15	19.4	29.7	15.5	44.6
Feb-15	19.1	28.9	15.6	42.5
Mar-15	20.2	28.1	18.9	41.2
Apr-15	20.8	29.6	18.1	43.2
May-15	20.8	32.0	*	*
Jun-15	21.7	33.9	17.5	41.3
July-15	21.9	38.2	18.6	45.2

*Data was lost during the month of May as central data device was disconnected.

3.2 Electricity consumption

To analyse the actual electricity usage of the houses a number of literature sources were used to establish typical electricity consumption patterns and benchmarks. A report completed for the Energy Saving Trust which presented the findings of a survey of electrical energy consumption in 251 households is used as a comparison [16]. The study found that average electricity consumption in households without electric heating was found to be 3638 kWh/year which when expressed in terms of average house floor area resulted in 65kWh/m^2/year. Another study of 27 households in Northern Ireland [17] found that annual electricity consumption had a strong relationship with the floor area of the building with the correlation equation presented:

$$49 \text{ x Floor Area in } m^2 + 233 = \text{electricity consumption in kWh} \quad (1)$$

The actual electricity consumption of the two monitored houses is presented alongside benchmark annual electricity consumption from previous literature [16], [17] in Table 2.

Table 2. Annual electricity consumption (kWh).

Electricity (kWh)	House 1	House 2
Actual	3094	3056
Zimmermann et al [16]	6685	3783
Yohanis et al [17]	5272	3085

House 1 consumes significantly less than benchmarks which may be explained by under occupancy. There are two occupants, one of whom is elderly and infirmed and the other a caregiver. Electricity usage in House 2 is in line with predictions.

Whist the amount of electricity consumed is significant when it is consumed is also of importance, particularly for demand side management applications. Figure 1 shows the average daily electricity profile in the two houses compared with the UK profile from the Energy Saving Trust [16]. The profile for House 2 appears to be relatively high overnight which could be explained by occupiers working shift patterns. The load profile for House 1 is lower than literature sources again possibly explained by under occupancy.

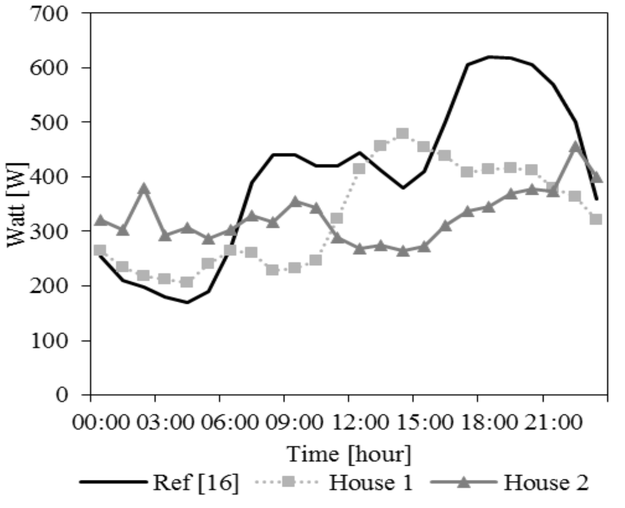

Figure 1. Average daily electricity profile of both properties compared to the UK profile obtained from [16].

3.3 Gas consumption – space heating and domestic hot water

Space heating and domestic hot water is supplied to both properties by a gas condensing boiler. The average daily domestic hot water usage was 99 litres and 216 litres for House 1 and 2 respectively. Average domestic hot water usage in a UK study of a 124 homes has been previously reported as 121 litres. The significant difference between this UK average and house 2 is being investigated further.

Monthly gas consumption for the two properties are shown in Table 3.

Table 3. Monthly gas consumption.

Gas (kWh)	House 1	House 2
Aug-14	489.3	158.7
Sep-14	263.3	415.1
Oct-14	1184.0	552.7
Nov-14	1820.5	1150.6
Dec-14	2768.6	1701.2
Jan-15	3290.0	1386.5
Feb-15	2720.2	988.7
Mar-15	2437.7	907.9
Apr-15	1244.8	583.0
May-15	1136.4	49.1*
Jun-15	361.2	61.4*
Jul-15	252.7	284.5
Total	17968.8	8239.2

*Data was lost during the month of May and start of June as central data device was disconnected

4 MODELLING OF CASE STUDY PROPERTIES

Integrated Environment Solutions Virtual Environment (IES-VE) is a dynamic energy simulation modelling tool. It has been validated for a number of national and international standards such as ASHRAE 140:2007, CIBSE TM33 and ISO7730 [18] and has been found to have energy predictions in line with other dynamic simulation tools in standard scenarios. AutoCad drawings of the two houses were converted to DXF file formats and imported into IES-VE and traced to create the geometry of the building as shown in Figure 2.

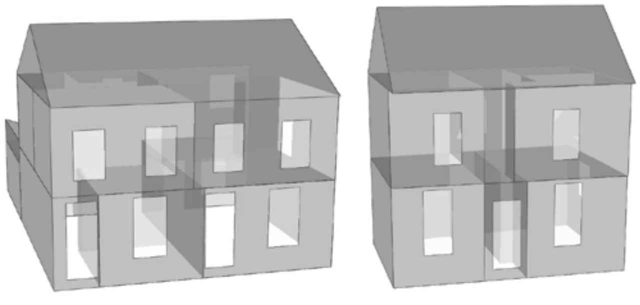

Figure 2. Case study properties geometry modelled in IES-VE. House 1 shown on the left and house 2 is on the right.

Thermal properties of the building envelope, heating profiles, infiltration/ventilation rates and temperature set points were included and are detailed in Table 4.

Table 4. House summary & IES-VE model inputs.

Description	Unit	1	2
Roof U-value	W/m^2K	0.16	0.16
Floor U-value	W/m^2K	0.22	0.22
Wall U-value	W/m^2K	0.22	0.45
Window U-value	W/m^2K	3.10	3.10
Door U-value	W/m^2K	2.2	2.2
Air-tightness	$m^3/hr.m^2$ at 50 Pa	15.04	10.52
Floor area	m^2	102.9	58.2
Occupants	No.	2	2
Occupancy type		24 hours	Shift workers
DHW average daily consumption	Litres	99	216
Set point temperatures	ºC	19	18
Heating profile		6am – 10pm	6am – 8am & 6pm-10pm

4.1 *Model calibration*

Until relatively recently calibration of models to measured results often relied on a trial and error approach, highly dependent on user knowledge, experience and statistical expertise [19]. Modelled and measured data were often compared using simple methods such as percentage error. These methods however could result in a compensation effect with overestimations cancelling out underestimations [19]. Two dimensionless error indices are recommended by a number a guidelines [19-21] to calibrate a building energy model: Mean Bias Error (MBE) (%) and Co-efficient of Variation of Root Mean Square Error (CVRMSE) (%). Models may be calibrated on a monthly or hourly basis. Mean bias error calculates the mean difference between measured and simulated data and is considered a good indicator of model bias. However this index allows for a cancellation effect of negative bias cancelling out positive bias and therefore an additional method of error measurement is required. Root mean square error (RMSE) (%) measures the variability of the data. It is the calculated difference between measured and simulated data points which is then squared. The squared errors are summed for a period and divided by the number of values taken. A square root is then taken of this result. By investigating the co-efficient of variation of root mean square error the accumulated magnitude of error of a model can be established. The CVRMSE does not suffer from the same cancellation effect as MBE, and is overall a better measure of the prediction accuracy of the model. A summary criteria for calibration on a monthly basis as recommended by three guidance documents is provided in Table 5.

Table 5. Monthly calibration criteria recommended by literature.

Monthly criteria (±%)	MBE	CVRMSE
ASHARE 14 [20]	5	15
IPMVP [22]	20	
FEMP [21]	5	15

The short-comings of these criteria have been detailed by [19], but they do not consider any inaccuracy associated with input parameters and consider energy consumption only, ignoring the simulation of internal conditions such as temperature and humidity. Given the relatively wide acceptance criteria range it is possible that numerous models of the same building could be considered calibrated.

In this paper calibration of gas consumption, for space heating and domestic hot water, was carried out on a monthly basis. Electrical energy consumption was not included in this paper as it currently only represents approximately 15% of total household energy use and can be highly occupant dependent [23] .

Gas consumption measured and modelled for House 1 had an MBE and CVRMSE 0.6% and 12.0% of respectively. Gas consumption measured and modelled for house 2 had an MBE of 0.4% and CVRMSE of 14.9%. Figure 4 shows the modelled and measured gas consumption on a monthly basis for House 1 and 2.

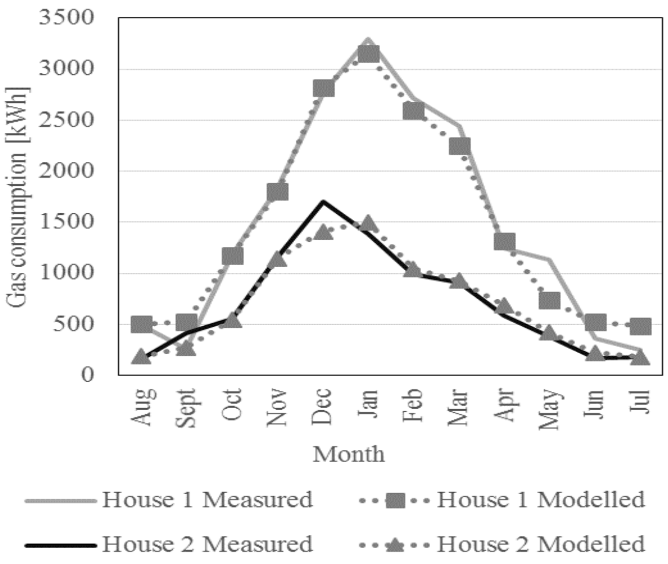

Figure 3. Monthly measured and modelled gas consumption for case study properties.

Whilst weather data was gathered at a local weather station during the monitoring period a weather file for central Belfast from the Prometheus project [24] was used. Using the local weather data may have allowed for better model calibration with improved MBE and CVRMSE values however the use of previously agreed reference files also allows easier cross referencing by other researchers.

4.2 *Climate change projections*

Climate projections in the UK have been funded by Department for Environment, Food and Rural Affairs

(DEFRA) and produced by the Met Office with all information made available on the UK Climate Projections (UKCP09) website. In UKCP09 the climate change projections may be generated from three different emissions scenarios and are available for three different years: 2030, 2050 and 2080. The three emissions scenarios are those developed in Special Report on Emissions Scenarios (SRES) produced by the IPCC Intergovernmental Panel on Climate Change in 2000. The scenarios are based on different rates of economic and social change covering items such as population change, economic growth, technologies and energy intensity of the 21st century. There is a high (SRES A1F1), medium (SRES A1B) and low (SRES B1) emissions scenario. Given the current trend of emissions, only the high emissions (A1F1) scenario has been included in this paper. It should be noted that other scenario will have less of an impact of overheating and therefore A1F1 provides the worst case position to judge the suitability/effectiveness of retrofit design

To take into account the natural variability and uncertainty associated with climate results of whichever emission scenario or year selected, UKCP09 presents the projections with the probabilities of a range of possible outcomes. The climate data is issued as a probability density function resulting in a range of percentiles; 10, 33, 50, 66 & 90. It is important to note as explained by [25] that these probabilities are subjective having been estimated from the strength of existing information and are not objective estimates that account for all possible results. Whilst modelling should be completed for the range of risk as per previous studies outlined in [14], only the 90 percentile is used in this paper to establish the maximum potential risk and impact.

Using the information generated by UKCP09, the Prometheus project [24] have created weather files in the Energy Plus format that can be imported and used in most building simulation software. Weather files for forty five locations have so far been created, of which two are in Northern Ireland; Belfast and Derry/Londonderry. The files are available for three future time periods 2030, 2050 & 2080 with three emissions scenarios. Two weather file types are available from the Prometheus project, as discussed by [24], Test Reference Years and Design Summer Years. Test Reference Year (TRY) weather files are made up of months from different years and do not contain extreme heat-waves therefore are considered unsuitable for overheating risk assessment. Design Summer Years (DSY) are used for summer overheating assessment only and are based on average temperature of the summer months at the centre of the upper quartile of rankings obtained from approximately 20 individual years. Design summer year (DSY) weather files will be used to examine risk of overheating whilst test reference years will be used to examine any shifting pattern of energy loads for space heating with the properties. Internal set point temperatures and average domestic hot water consumption were assumed to remain at current levels in future climate scenarios.

4.3 *Overheating in case study properties – current and future climates*

Using the design summer year weather files for the high emissions scenario (A1F1) and the 90 percentile, overheating in the bedroom and living room was assessed for current and future climate scenarios. Only natural ventilation was included within the model as during site visits it was found that the installed MVHR systems were not active. The CIBSE criteria [12] for summer overheating were used as guidance with results summarised in the Table 6.

There is a difference between the measured and modelled internal temperatures in House 1; notably the measured internal temperatures in the bedroom only exceed 26°C for 0.4% of the time during monitoring period whereas the model reported 6.1% exceedance. Further model calibration including any adaptive behaviour taken by occupants and local weather file may reduce this difference. The measured and modelled results align better in the case of House 2.

Table 6. Percentage of hours of overheating in bedroom and living room - measured and modelled.

% time temperature exceeded	Bedroom exceeds 26°C		Living room exceeds 28°C	
	House 1	House 2	House 1	House 2
Measured	0.4	0.2	0	0
Current modelled	6.1	0.1	0	0
2030	30.4	1.7	1.3	0
2050	36.7	6.2	7.3	0.2
2080	43.9	21.5	16.2	8.3

As external summer temperatures increase as per changing climate scenarios in 2030, 2050 and 2080, there is an increase in the amount of time internal temperatures exceed the 1% guidance. House 1 appears to be at a higher risk of overheating in future climate scenarios with living room and bedroom temperatures exceeding guidance criteria 16.2% and 43.9% of the time. Given the high rates of overheating it is likely that House 1 would require mechanical cooling or significant physical interventions such as solar shading to ensure comfortable internal temperatures.

It should be noted that these figures do not account for any adaptive behaviours that occupants are likely to employ. Occupants are not passive and will make adjustments to window/blinds and clothing levels, which would be influential in alleviating overheating.

4.4 *Gas consumption in case study properties – current and future climates*

Annual gas consumption for space heating and domestic hot water measured and modelled in current and future climates for both case studies is shown in Figure 4. Test reference year weather files were used within the models. As the climate changes, with winters becoming milder, the need for space heating dramatically declines with House 1 consuming 44%

less gas in 2080 than in 2015 and House 2 consuming 47% less gas in 2080 than in 2015.

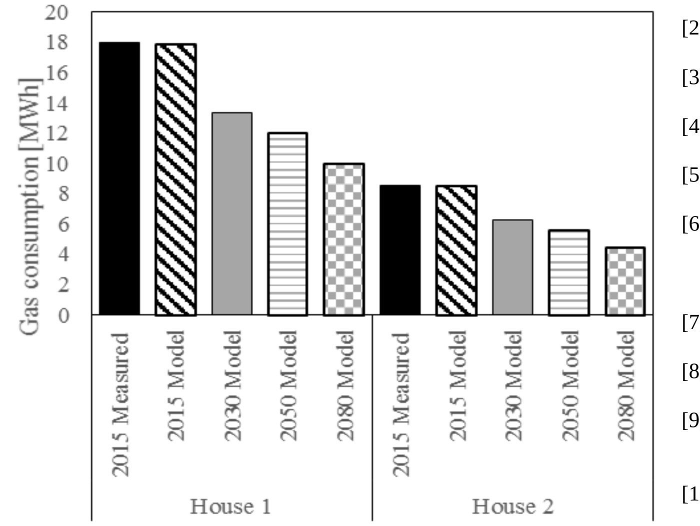

Figure 4. Gas consumption in House 1 and 2 - measured and modelled for current and future climate scenarios.

4.5 Cooling energy demand in future climate scenarios

Under the modelled scenario House 1 is likely to require mechanical cooling. To investigate the effect of implementing mechanical cooling House 1 was modelled for 2080 with a set point of 25°C. This resulted in a cooling demand of 2.81 MWh.

5 CONCLUSIONS

Modelling the retrofitted case study properties for future climate in 2030, 2050 and 2080 has shown a significant reduction in gas consumption and increased levels of summer overheating.

The need for cooling, a significant source of carbon emissions, must be considered in any retrofit strategy. Whilst emphasis should be placed on reducing heat demand during winter months the consequences of ignoring the changing climate would be significant. The study shows that such short term measures would result in future interventions that will be both costly and environmentally damaging. The future climate scenarios modelled were based on the high emissions scenario at the 90th percentile, this is the worst case scenario. Further iterations of the model should be undertaken at the lower percentiles to understand the range of risk. Further work will be undertaken to establish what effect reasonable interventions such as addition of solar shading and occupancy behavioural change will have on internal summer temperatures.

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