Investigating the Potential of Retrofitting and Onsite Renewable as a Pathway to Zero Carbon Emission in Dwellings

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Abstract

Buildings are responsible for half the energy consumptions and carbon emissions in the UK and since about 75% of the year 2050 building stock already exist considering the current rate of demolition and new building, reducing carbon emission from existing buildings is therefore crucial to meeting the UK target of 80% carbon emission reduction by 2050. This work described simulation results of the potentials of refurbishing existing dwellings using existing technologies to achieve a low carbon emission. A base-case scenario was modelled of a semi-detached house with un-insulated cavity wall, timber floor and loft, single glazing, low air change rates, high indoor temperatures, and low efficiency gas boiler. This baseline was incrementally up-graded to higher energy performance standards. The energy consumption and carbon emission of 24,909 KWh pa and 5161 KgCO2 pa of the baseline case fell to 5,421 KWh pa and 716 kgCO2 pa respectively representing more than 60% cut in carbon emission. The research demonstrated that a large reduction in energy use and carbon emissions is possible using existing technologies and adapting to lower indoor temperatures.

Keywords: Building Energy Consumptions; Building Carbon Emission; Domestic Buildings; IES Software; Retrofitting pathways.

1.1. Introduction

According to the government definition; a zero carbon home is one with 'zero net emission of carbon dioxide (CO_2) from all energy use in the home [DCLG 2006]. To achieve this standard, such home will have high thermal insulation, use natural light and ventilation, adopt passive heating, use low energy appliances and lights to reduce its energy use and CO_2 emission. Importantly, it must also meet any remaining energy requirements from renewable energy sources. It is notable to emphasise that even where all these measures are achieved, the nature of human interaction with these technologies will be a critical success factor in mitigating CO_2 emission.

The gains accruing from reducing energy use and CO_2 emission and also replacing fossil fuels with renewable energy sources are enormous; reduction in global warming, increasing security of fuel supply, reduction in fuel poverty, creation of more jobs, promotion of the local community and sustainability are some of the obvious gains. These gains ensure that we "meet the needs of the present without compromising the ability of future generations to meet their own needs" [Brundtland 1987].This study used state of art dynamic building modeling tools to quantify the benefits of onsite renewable technologies (in addition to other energy saving retrofitting measures), towards achieving the UK 80% CO_2 emission reduction targets in dwellings. It also predicts how some adaptive changes in occupant's behaviours could impact on this prospective emission target.

1.1.1. Carbon Emission

Atmospheric concentration of carbon dioxide as shown in *figure 1* is at its highest for at least 650,000 years. The current stock of the gas in the atmosphere is equivalent to around 430 parts per million (ppm), compared with only 280 ppm before the industrial revolution. This rising concentration has already caused the world to warm by 0.74°C in the last century and will lead to at least a further half degree of warming over the next few decades [ICPC 2007].

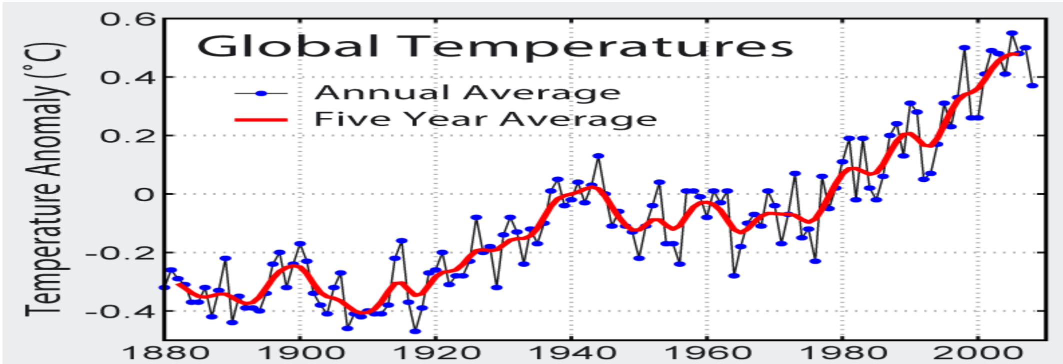

Figure 1. *The rise in global average temperatures (Goddard Institute for Space Studies)*

The Committee for Climate Change (CCC) advised that the world needs to aim to limit temperature increases to 2°C, and to ensure that the chance of a 4°C increase rarely occurs. Failure to do this would result in adverse environmental impacts with significant human consequences like the melting of the Greenland ice caps, extinction of large numbers of animal species, flooding, extreme weather events, ocean acidification and reduction in crop yields [CCC 2008].

1.1.2. The UK's Response

In October 2008, UK became the first country in the world to set an ambitious legally binding target, aiming to reduce greenhouse gas emissions by 80% by 2050 relative to the 1990 level [DEFRA 2008]. The scale of this challenge is enormous (*figure 2).*

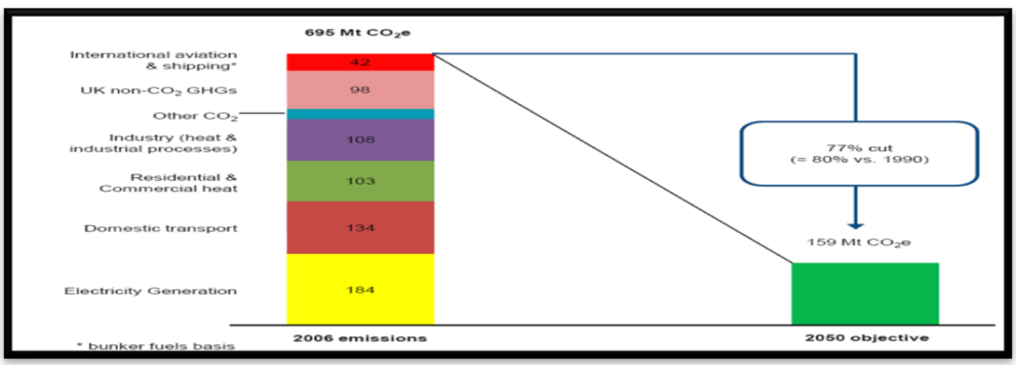

Figure 2 *The scale of the challenge (Sourced CCC 2008)*

1.1.3. Energy Use in UK Homes

The UK's housing stock is among the least efficient in Europe. About one-third of energy used in houses is wasted due to inefficiency. Out of the 25 million households, 2 million are classified fuel poor. Buildings consume about 47% of the total delivered energy. Domestic buildings account for 64% of the total energy to buildings [DTI 2006]. Energy is used in dwellings to cater for space heating, hot water, lighting and power to appliances. Up to 83% of energy used in households is for space and water heating; these are highly dependent on changes in external temperatures and the efficiency of the building fabric. Energy consumption for space heating increased by 28%, water heating by 8%, and lighting and appliances by 150% since 1970 [DECC 2008]. In about 86% of the UK houses (18.9 million), natural gas provides the fuels for space and water heating, while the remaining households use electricity [BRE 2008]. These shows that there are great opportunities to reduce carbon emission particularly if fossil energy sources are replaced with a renewable energy sources, lower carbon intensive electricity is used to operate electrical lights and appliances and if the building fabrics are made more thermally efficient.

1.1.4. Previous Research on Low Carbon Dwellings

Yao et al [Yao 2005] developed a simple dynamic model for generating UK domestic energy load profile calibrated in the current trends in energy consumption called the SMLP. 'Cluster analysis' method was applied based on some typical scenarios of occupancy. This model does not account for carbon dioxide emissions and so could not inform us on what manner of emission savings could accrue from retrofitting the building fabric and from onsite renewable.

The model's predictive capacity was not explored beyond the requirement for initial design and planning for renewable energy systems and so does not venture to paint any future scenario. Undoubtedly, Boardman's 40% House [Boardman 2005] built upon the UK Domestic Carbon Model (UKCDM) an upshot of BRE Domestic Energy Model (BREDEM) provides a strong theoretical base that could be explored to achieve the 60% reduction in carbon emission. To achieve this target reduction in existing dwellings, Boardman argues that these dwellings must be upgraded to reduce heating demand to 6500 kWh pa and this will requires a "90% insulation of all cavity walls, 30% of all solid walls, 100% loft insulation (up to 300mm) 100% high performance doors and 90% high performance windows". While this proposal is significantly tight, it does not foreclose exploring other energy and emission saving retrofitting measures that could be applied to existing dwellings, for example; advanced glazing, duct insulation and the use of controls in regulating the temperature hot water supply, boiler sequence control etc. Therefore, in the author's words; "the scenario in the *40% House* concept is acknowledged to be a 'best guess'" and is therefore in need of refinement through further discussion and research". Again with the new government set target of achieving an 80% reduction in carbon emission by 2050 against the 1990 levels, there is now a need for the '20% house' scenario'.

Firth *et al* [Firth et al 2008a] in justifying the need for Community Domestic Energy Model (CDEM) opined that the four existing housing stock models; UKCDM, BREHOMES, DECarb and Johnson's model, are either "not available publically or the implementation of the models is very complex and not transparent". Furthermore, the authors observed that "assumptions used and algorithms employed are impractical". The CDEM was therefore put forward to "address the current lack of knowledge concerning the accuracy of the UK domestic housing stock models and the uncertainty in their predictions, to quantify the relative impact of different CO_2 reduction measures and to pave the way to greater transparency in energy modelling through the development of simple models". This model studied and made predictions on CO_2 emission savings due mainly to energy efficiency measures like 100% of solid wall insulation, cavity wall insulation, gas boilers as condensing, double glazing, 0.5 ach ventilation rate, 300mm loft insulation, water heating interventions, low energy cold appliances, low energy lights and standby power appliances and reported an overall savings of between 35% – 45% based on the 2001 levels [Firth et al 2008b]. All the models except that of *Yao et al* used in the above mentioned exercises were steady state models based on the BREDEM model; this work used established dynamic models from contemporary simulation packages, the Integrated Environmental Solutions (IES) [IES 2009] to quantify energy benefit in retrofitting pathways. The IES Virtual Environment is a dynamic thermal simulation tool based on the first principles mathematical modeling of the heat transfer process. It has passed the ASHRAE Standard 140 test and qualifies for the CIBSE standard for dynamic model [Crawley 2005].

2.1. Materials and Method

2.1.1. Model Description

The building modelled in the IES for this study is a south facing, 2 storey semi-detached dwelling comprising of 3 bedrooms and a bathroom on the upper floor and hall, dining room, living room and kitchen on the ground floor. It has a total volume of 213.9 m^3, floor area of 85.6 m^2, external wall area of 99.25 m^2 and external opening area of 13.4 m^2. The diagram of the modelled building is shown in *figure 3.* A highly insulated wall (not shown in the figure) with no heating was added to the eastern wall to simulate a party wall.

Figure 3. Picture of the modelled semi - detached building

2.1.2. Methodology

The building fabric and glazing was upgraded (Table 1 & 2). A base case scenario was modelled of a semi detached house with un-insulated cavity wall, timber floor and loft, single glazing, 1.5 ACH rates, high indoor temperatures (21^{o}C and 18^{o}C for living room and other room respectively), and 70% efficient gas boiler. This baseline was incrementally up-graded starting with fabric insulation, energy efficient glazing *(Table 1 & 2)*, 0.5 ACH rates, reduction in indoor temperatures, 88% efficient gas boiler, solar hot water and replacement of natural gas fuel with biomass.

	Base-case	**Target-case**
Site definition	25m high, 51.48^o N & 0.45^o W	25m high, 51.48^o N & 0.45^o W
Type of dwelling	3 bedroom semi-detached	3 bedroom semi-detached
Building fabric	Un-insulated	Insulated
Ventilation	1.5 ACH	0.5 ACH
Heating system & hot water heating	Good existing gas boiler with 70% seasonal efficiency	Biomass fired boiler with 88% seasonal efficiency
Domestic Hot water	Using main heating system	Using solar heating
Miscellaneous	Same	Same
Lighting	Same	Same
Standard Occupancy	3 people	3 people

Table 1. Summary of information used to describe the base and target case scenario

Existing construction element	**Base case U-values W/m^{2}K**	**Improvement measures**	**Achieved U values /m^{2}K**
Cavity wall external	1.43	Filled cavity with insulation	0.35
Roof	3.38	Insulate first layer between joist and second layer across joist	0.16
Floor	0.63	Insulate between joist of timber and above concrete floor	0.23
Glazing	5.17	Replace with high performance window	1.98

Table 2. Base and test case thermal transmittance value

3.1 Discussions of Results

3.1.1. Base case

Table 3 shows the energy consumption (kWh/year) and the corresponding CO_2 emissions (kgCO_2/year) due to the use of fuel and electricity to heat the home under the base case scenario. The value of total fuel energy use of 24,909 kWh and CO_2 of 5,161 kgCO_2 is within the range of values derived from other works for semi detached building of similar energy profile. For example CDEM model [Firth et al 2008] reported an average energy use of 23,897 kWh and a CO_2 emission rate of 5,776 kgCO_2 for a semi-detached house. Carbon Trust Project monitoring report by Cambridge Architectural Research [CT 2006] stated a UK housing average of 273 kWh/m^2/year energy consumption and 44.7 kgCO_2/m^2/year for carbon emission which is 23,360 kWh/year and 3,825 kgCO_2/year when applied to our case.

Letcher (2005) reported a stock average of 324 kWh/m^2/year and 71 kgCO_2/m^2/year which in our case will amount to 27,720 kWh/year and 6074 kgCO_2/year for fuel energy consumption and CO_2 emission respectively [Letcher 2005]. Lastly Energy Saving Trust in its publication listed the fuel energy use and CO_2 emission for a typical cavity walled semi-detached house under its own base case scenario as 25,600 kWh/year and 5,660 kgCO_2/year respectively [EST 2006]. All these results show that our baseline figures for fuel energy consumption and CO_2 emission are within the range of averages reported in other works. The differences may be because the buildings models used in the other works are of slightly different geometric and physical parameters.

It may also be as a result of the different accounting system and model calibrations employed by each work. The above results are validation of our base case scenario.

Date	Total Fuel energy (MWh)	Total Fuel carbon emission (CE) (kgCO2)
Jan 01-31	4.40	883
Feb 01-28	4.12	826
Mar 01-31	3.57	723
Apr 01-30	2.38	491
May 01-31	0.13	50
Jun 01-30	0.13	48
Jul 01-31	0.13	49
Aug 01-31	0.13	50
Sep 01-30	0.13	48
Oct 01-31	2.57	529
Nov 01-30	3.04	620
Dec 01-30	4.19	843
Total	24.91	5161

Table 3. Annual fuel energy use & CO_2 emissions for base case

3.1.2. Test Cases

Table 4, figure 4, 5 and 6 highlights the relative savings in fuel energy use and CO_2 emission due to incremental upgrade of the modelled building from the base case scenario. It can be seen that mostly both energy use and CO_2 emission reduced with each upgrade. *Figure 4 and 5* showed that energy consumption and CO_2 emission is highest in January for all the cases investigated, this gradually reduced and finally converged at its lowest point at the beginning of May till the end of September when the heating system is off and whatever energy consumption and carbon emission remains is that due to hot water demand and lighting/appliances gain (this is fairly uniform throughout the year). This profile is typical of UK climate, coldest in January requiring more heating. Less heating is required in spring and autumn and no heating during summer.

Cases	**Fuel Energy consumption (kWh/year)**	**Savings in fuel energy (kWh/year)**	**CO_2 Emission (CE) ($KgCO_2$/year)**	**savings in CE due to improvement ($KgCO_2$/year)**	**% Reduction in CE against Base case**
Base	24909	-	5161	-	-
A = Cavity Insulation	19635	5274	4137	1024	19.84
B = A + floor insulation	18347	1288	3887	250	24.69
C = B + loft insulation	15486	2861	3332	555	35.44
D = C + low e-double glazing	14387	1099	3119	213	39.57
E = D + Lower indoor temperatures	11289	3098	2518	601	51.21
F = E + Lower ACH	6652	4637	1619	899	68.63
G = F + Boiler efficiency (88%)	5586	1066	1412	207	72.64
H = G + Solar hot water	5421	165	1385	27	73.16
I = H + Replacing gas with biomass	5421	0	716	669	86.13

Table 4. Cases results for fuel energy consumption and CO_2 emission

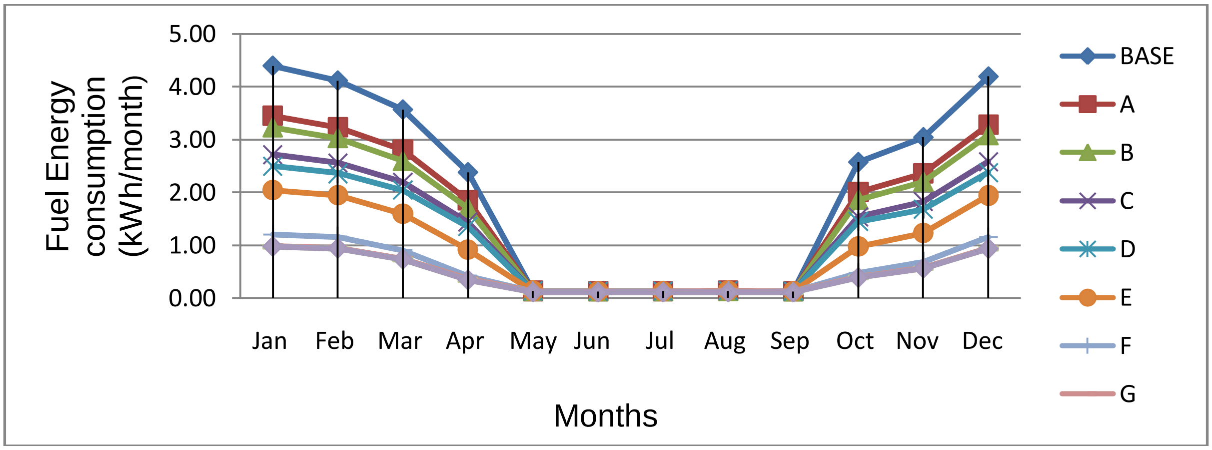

Figure 4. Profile of annual fuel energy consumption for each upgrade (A-I)

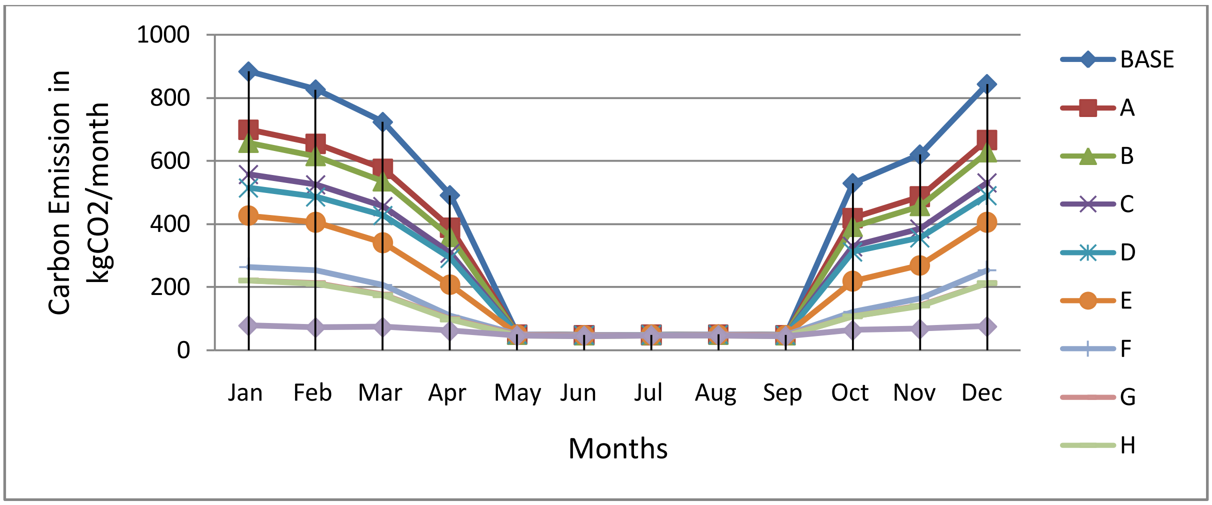

Figure 5. A graph of annual CO_2 emission for each upgrade (A-I)

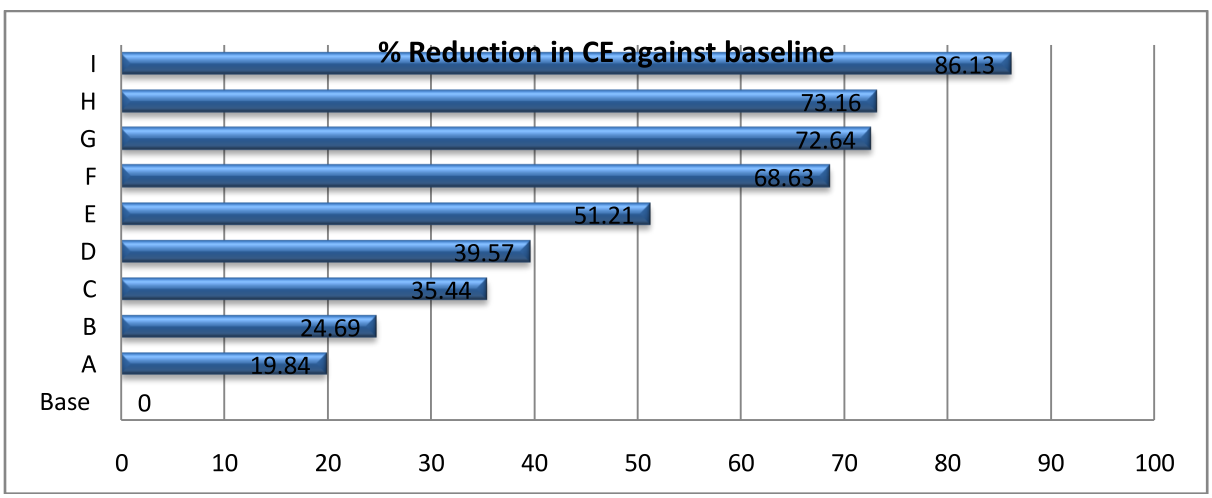

Figure 6. Chart showing % of CE reduction against each cases

The results also showed that the use of renewable energy or technology may not necessarily result in energy savings, as has been demonstrated when natural gas was replaced with biomass, the fuel energy use remain unchanged at 5,421 kWh pa, but results in great savings in CO_2 emission. Building fabric insulation made the greatest contribution to energy savings. Interestingly, lowering indoor temperatures and ventilation rate seems to make even greater contribution to energy savings than upgrading the efficiency of boiler.

However, care should be taking not to over stretch the significance of savings that can be attributed to an individual component upgrade, each upgrade completely alters the dynamics of the building and so any savings made is a cumulative which includes other earlier upgrade. For example, the savings made when the building is leaky even when the boiler efficiency is upgraded is less compared to when an efficient boiler is used in well insulated house. It was observed that when the sequence of upgrade was altered from the one presented in this work, the savings from each individual upgrade is different from the ones shown in *table 4*. However, interestingly it was also observed from some trial simulations that no matter what sequence were followed and although the saving accrual due to individual upgrade is different for each route, the sum of the savings is roughly the same. As can be seen in *Figure 6*, in addition to other upgrade measures, great savings in CO_2 emission was achieved in the decarbonising of the fuel used from natural gas to biomass. It is reasonable to expect that similar savings in CO_2 emissions should be obtained if other non fossil fuel such as hydrogen is used to replace natural gas as a domestic fuel. Total CO_2 emission savings due to solar hot water appears small but since hot water energy demand is often about 20% of the total energy demand, the low value of savings may not be out of place. Therefore, through the use of various energy efficient interventions (fabric insulations, energy efficient glazing, reduction in indoor temperatures and ventilation rates and upgrading boiler efficiency) and the use of onsite renewables (solar hot water and biomass fired boiler), the building energy use and CO_2 emissions was reduced from the base case 24,909 kWh pa and 5,161 kgCO_2 pa to 5,421 kWh pa and 716 kgCO_2 pa respectively. An energy demand of 6,500 kWh pa in a dwelling will qualified it as a 40% house [10]; our final test case dwelling has surpassed this threshold.

4.1. Conclusions

A base case scenario was modelled of a semi detached house with un-insulated cavity wall, timber floor and loft, single glazing, 1.5 ACH rates, higher indoor temperatures, and 70% efficient gas boiler. This baseline was incrementally up graded starting with fabric insulation, energy efficient glazing, 0.5 ACH rates, reduction in indoor temperatures, 88% efficient gas boiler, solar hot water and replacement of natural gas fuel with biomass.
The energy consumption and CO_2 emission of 24,909 KWh pa and 5161 KgCO_2 pa of the baseline case was reduced to 5,421 KWh pa and 716 kgCO_2 pa respectively. Decarbonising heating by replacing natural gas with biomass does not result in any energy saving even though it has substantial effects on CO_2 emission reduction. This means that a more complete effort at reducing CO_2 emission should combine both energy efficiency measures and the use of renewable.

The human side investigated in this research is adapting to a lower indoor temperatures and lower ventilation rates. The study revealed that both have significant effect in cutting down fuel energy use and CO_2 emission.
Performance of the building fabric, boiler efficiency, heating demand reduction and type of fuel use coupled the right human behaviour are key factors in the rate and extent of achieving low or zero carbon in dwellings.
The research has demonstrated that a large reduction in energy use and carbon emissions is possible using existing technologies and adapting to lower indoor temperatures. This research has proved the potential of energy efficient measures and onsite renewable technologies for low or zero carbon emission in UK dwellings. Further research could investigate further cutting down CO_2 emission through the decarbonising of electricity and upgrading of boiler beyond 88%.

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