Assessing Residential Retrofit Measures to Reduce the Risk of Fuel Poverty: A Modelling Approach at Community Scale

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Abstract

This work focuses on a modelling-led approach regarding the impact of different retrofit measures on limiting the risk of fuel poverty within a grid-constrained community. 102 house archetypes are selected to represent 322 existing dwellings located in Orkney, Scotland. Archetyping is based on a parametric housing stock energy model using GIS (Geographic Information System) data and EPC (Energy Performance Certificate) datasets (or equivalent) to automatically generate house models suitable to be studied using the EnergyPlus dynamic simulation engine. The sensitivity of each house archetype to fuel poverty risk is evaluated for different household's income bands. When all houses are assumed to belong to the lower income band, the application of a full fabric retrofit package results in limiting fuel poverty risk from 46.1% to 21.6% within the modelled community. Only 4.2% of the houses still remain vulnerable to fuel poverty when a full fabric plus heating system retrofit package is applied.

Introduction

Fuel poverty is an issue of social inequality and injustice (Walker and Day, 2012) firstly brought to public attention by Boardman in 1991, who defines a household as fuel poor if it is "*unable to obtain an adequate level of energy services, particularly warmth, for 10 per cent of its income*". Ten years later, the UK Government, (adopting Boardman's definition) published the first official document (2001 UK Fuel Poverty Strategy) acknowledging that fuel poverty is a policy matter requiring governmental intervention. Since then, the frame under which a house is defined as fuel poor has been subject to much criticism with the current situation being different across the UK. More specifically, while England uses the low-income-high-cost indicator to evaluate fuel poverty, Scotland, Northern Ireland and Wales has maintained the 10% definition.

In addition to the 10% threshold, the 2019 Act in Scotland considers a household as fuel poor if its residual income (after deducting fuel and housing costs) is less than 90% of the minimum income standard (Scottish Government, 2020a). The same document also sets three targets for 2040 as follows; no more than 5% and 1% of households should be in fuel and extreme fuel poverty, respectively and the median fuel poverty gap of households in fuel poverty should be no more than £250 in 2015 prices. These particular targets refer to Scotland as a whole as well as to each of the 32 local authorities separately. Based on the 2018 Scottish House Condition Survey (SHCS)[1], 25% of households in Scotland were estimated to be in fuel poverty, whilst another 11.3% in extreme fuel poverty (Scottish Government, 2020b).

Although fuel poverty is a well-established socio-economic phenomenon in the UK, the strategy that the Government will follow to achieve these ambitious targets is yet unclear. Amongst others, the Scottish Government highlights the need for involved ministries to clarify how they "*intend to identify households in fuel poverty"* and states that fuel poverty strategy must "*identify characteristics of households which are likely to be in fuel poverty or for which getting out of fuel poverty presents particular challenges*" (Scottish Government, 2019). Indeed, the delivery of an effective fuel poverty strategy does significantly depend on the establishment of a sophisticated approach capable of identifying those most in need and thus, preventing targeting the "wrong" households or excluding groups considerably vulnerable to fuel poverty.

From its definition, fuel poverty is a multidimensional problem with low income, poor energy efficiency and increased energy prices being its key drivers. These interacting and dynamic fuel poverty factors suggest that any household has the potential to move in and out of fuel poverty status at any time and for different reasons. The inherently complex nature of fuel poverty makes it difficult for policy to tackle. To safely conclude whether a household is fuel poor, a full property and income assessment is required. However, this would be an expensive, time-consuming or even intrusive task to be carried out at the national scale. Instead, several indicators acting as *proxies* are currently employed by policy to identify and support households at higher risk for fuel poverty.

Indicators of fuel poverty

To date, there are mainly two fuel poverty related schemes in Scotland, both being under the umbrella of HEEPS (Home Energy Efficiency Programmes for Scotland).

[1] SHCS statistics included in this work are not fully compatible with the current definition of fuel poverty (as included in 2019 Act in Scotland).

Warner Homes Scotland scheme (HEEPS:WHS) follows an income-based targeting approach and as such, it is eligible for low income households including elderlies (over 75), households with children under 16 and occupants with a particular disability (all in receipt of qualifying benefits). This targeting approach is in accordance with the findings of the 2018 SCHS based on which 95% and 55% of the first and second bottom income band, respectively, were identified as fuel poor. Since 2013, over 20,000 households have received support for upgrading insulation (either wall or loft), replacing their heating system, installing renewables or adopting draught-proofing measures (EST, 2020a). This income-based targeting is undeniably an important step to alleviate fuel poverty (or, in some extent, improve the living standard of those most in need). Nevertheless, it does not necessarily capture those being in fuel poverty based on the 10% definition. In other words, a household might not be eligible for support even if its energy costs are higher than 10% of its total income (e.g. living in a thermally inefficient house or obliged to be at home all day). In addition to that, such a targeting approach might exclude groups sensitive to specific fuel poverty factors. Roberts *et al.* (2015) showed that *rural households* (and especially those being off the gas grid) are more vulnerable to fuel poverty at periods of rapid energy price rises, this being associated with constraints they often experience in choosing heating system or changing their fuel supplier. Another factor being reported as a significant fuel poverty driver is *under-occupancy*, this being found to have a greater effect for detached and energy inefficient houses (Scottish Government, 2017).

Area Based Schemes (HEEPS:ABS) (which by definition follow an area-based targeting approach) are designed to provide support for fuel poor areas (Scottish Government, 2019). They focus on upgrading insulation and especially, for those hard-to-treat properties, where wall insulation is a comparatively expensive intervention. 66% of these hard-to-treat houses were reported to be in fuel poverty (Dowson *et al.,* 2012). The utilization of the Scottish Index of Multiple Deprivation (SIMD) is often employed as a proxy for the identification of fuel poor areas, this being a relative measure of deprivation provided at data zone level [1] that evaluates "*the extent to which an area is deprived across seven domains: income, employment, education, health, access to services, crime and housing*" (Scottish Government, 2020c). More specifically, each data zone is associated with a unique SIMD ranking score (1 corresponds to the most deprived and 6,976 to the least deprived area). However, evidence exists that although SIMD is suitable to be used for urban areas, it poorly captures fuel poor households of rural areas due to low housing density (Mould *et al.,* 2014).

In addition to that, information accessed through Energy Performance Certificates (EPCs) (or other equivalent datasets) combined with other income and demographic data sources can also be used to predict or estimate fuel poverty at the stock level (Vonnak and Zhao, 2020). However, although this approach benefits from the fact that EPCs are open source data registered at the individual house level, income and demographic data are usually available at a larger area level (e.g. lower super output areas for England or data zones for Scotland).

Retrofit

Large-scale retrofit has been identified as a necessity if the UK's 2050 target for net zero greenhouse gas emissions is to be met (CCC, 2019). In this context, area-based schemes have stimulated the roll-out of wall and loft insulation upgrades. However, it is more important now than ever to move toward the adoption of more radical retrofit solutions rather than just selecting energy efficiency measures that are capable of achieving the greater energy reduction at the lower cost. Area-based schemes should also include the deployment of low-carbon heating technologies such as heat-pumps and renewables in order for the UK to be on track for its long-term carbon emissions target. The latter is also of great importance for addressing fuel poverty in grid constrained areas.

Building stock models are effective tools to estimate the impact of mass retrofit on the community and city level and drive relative policy. Jones *et al.,* (2013) used a GIS-based model coupled with an embedded sub-model performing energy and carbon emissions calculations based on the UK Government's Standard Assessment Procedure to predict the impact of large-scale retrofit measures in Wales. In a similar way, Gupta and Gregg (2018) also developed a GIS-based model capable of evaluating the effectiveness of a wide range of retrofit measures at the city level. Following SAP calculations, the upgrade of cavity and solid wall insulation was found to be the most profitable retrofit from a carbon savings perspective for a neighbourhood in Bicester, UK, while a large-scale adoption of heat-pumps was not found to be a cost-competitive measure as the modelled area does mainly rely on the utilization of gas.

Objectives

In this work, a data zone in Orkney Islands is used as a case study area to investigate the extent to which both single and packaged retrofit measures can reduce the risk of fuel poverty. It should be noted at this point that the present work does not follow the official guideline for indicating fuel poor houses; this requires the estimation of the house's energy use based on BREDEM model[2] as well as the house's net income with the latter being impractical to be gathered for a fairly large number of houses. Using dynamic building performance simulation combined with national income data, the paper attempts to build up speed on identifying those characteristics that make a house vulnerable to fuel poverty. The modelled houses result from a residential building stock model adopting an

[1] Data zones are aggregates of Census Output Areas. They are designed to represent communities of 500-1000 household residents (large enough so that statistics can be well represented).

[2] Building Research Establishment's Domestic Model

archetyping approach based on GIS relating to geometry data and EPC datasets (or equivalent).

Methodology

Description of the case study area

The methodology developed for this work focuses on the simulated performance of 102 house archetypes, which are selected to represent 322 existing dwellings located in Kirkwall East, Orkney Islands, Scotland (north-east of Scotland). Orkney is a grid constrained region with excess electricity production from renewable energy sources. More specifically, Orkney accommodates the highest concentration of wind turbines in the UK supplemented by solar, wave and tidal energy. Orkney do currently produce around 130% of their own electricity needs. The work presented in this paper is part of a concerted effort focusing on creating a smart energy system for Orkney that incorporates a large number of electrified heating systems and that is capable of effectively balancing supply and demand. As such, there is a special focus on increasing the use of heat-pumps on the islands (replacement of both oil-fired boilers and conventional electric systems). At the same time, reducing fuel poverty is a strategic objective for the involved consortium as more than 60% of households in Orkney were estimated to be fuel poor with this figure rising to 85% for pensioner households (Orkney Islands Council, 2017).

The selected housing stock constitutes the *S01011824 data zone* including 16 unique postcodes in total (*Figure 1*). This area has a relative low SIMD score; 2,749 out of 6,976, which corresponds to the 4th decile).

Figure 1: S01011824 data zone, derived from Google Maps

Modelling approach

Archetyping is based on a parametric housing stock energy model capturing geometric and other house properties to automatically generate house archetype models, which are suitable to be studied using the EnergyPlus (E^+) dynamic simulation engine. 12 individual parameters are used in the current version of the model; these relate to dwelling's geometry (plan width and depth, dwelling height and other dimensional characteristics defining dwelling's shape) as well as number of storeys, roof pitch angle, built form (adjacencies), age of construction, wall construction type and heating system type. This information is being accessed through GIS data combined with data sets such EPCs and Home Analytics Scotland[1]. House models (each representing a particular house archetype) are automatically generated using an IDF (input data file) template. The residential stock model used for the purposes of this work including the archetyping process followed are explicitly described elsewhere (McCallum *et al.,* 2020). In the case of this study, the number of actual houses being represented by each archetype ranges from 1 to 20.

The modelled house archetypes have up to two storeys. At its current stage, the model considers that each floor is a unique thermal zone. The $U_{\text{-value}}$ of external walls is selected based on Table S7 included in the Appendix S of the UK Government's Standard Assessment Procedure (SAP). More specifically, as illustrated in *Figure 2*, the combination of wall construction type (solid, cavity, timber, system built) and age band of the dwelling is used as an indicator to assign the $U_{\text{-value}}$ of external walls. For example, for a solid brick house built before 1976 (age band A to E), the $U_{\text{-value}}$ of external walls is considered to be equal to 1.7 (no insulation). As EnergyPlus requires to specify detailed properties for the different building elements (e.g. walls), the materials layers and thicknesses are then selected for each different wall construction so that it is capable of achieving the corresponding $U_{\text{-value}}$. Similar approach is also followed for loft and ground-floor constructions, where U-values are selected based on the age band of the dwelling as suggested in RdSAP Tables S10 and S11, respectively (SAP, 2016).

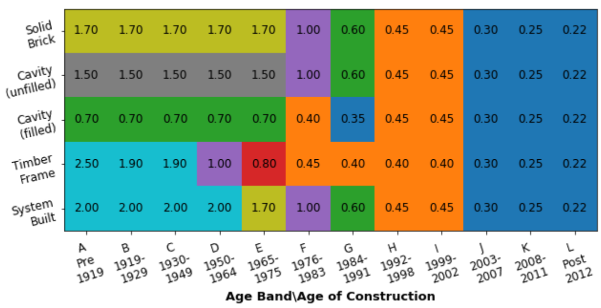

Figure 2: External wall $U_{\text{-value}}$ based on the dwelling's age band and wall construction type. Data derived from Reduced data SAP 2016 (SAP, 2016)

Future versions of the model will also account for window properties (e.g. single/double-glazed) and total glazing area. For the version used in this work, all windows are double-glazed, while glazing area is considered to be 25% of the total exposed wall area (for all the modelled house archetypes).

Heating is scheduled following the recommendations of the Scottish Government as included in the 2019 Act for

[1] Home Analytics (HA) a detailed dataset containing information for the Scottish housing stock provided down to the address level (EST 2020b)

fuel poverty (Scottish Government, 2020a). More specifically, heating system is modelled to be ON for 9 and 16 hours a day during the weekdays and weekend, respectively. It should be noted that based on the above document, indoor temperature is recommended to be 21°C for the living-room and 18°C for the rest of house. Nevertheless, as the model considers that every floor is a unique thermal zone, the heating set-point is considered to be 21°C for the ground-floor and 18°C for the upper floor for the case of two-storey houses, while for one-storey houses, heating set-point is regulated at 21°C for the entire house. The applied heating regime corresponds to typical households for which enhanced heating temperatures are not required (e.g. no elderlies or occupants with health issues are considered in this work).

Existing housing stock

Figure 3 illustrates the composition of the modelled house archetypes (at their current state) per built form and wall construction. Around 53% of the houses have uninsulated walls (belonging to age bands A,B,C,D,E). The most common dwelling type corresponds to 1950-64 (age band D) semi-detached house consisting of timber-framed walls with medium levels of insulation (U_{-value} = 1 W/m^{2}K).

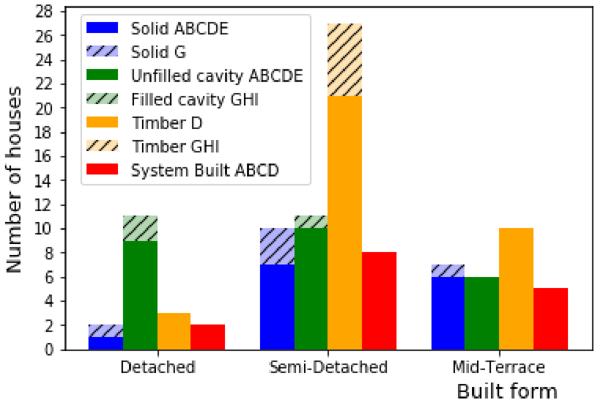

Figure 3: Number of house archetypes per built form and wall construction

The houses meet their space-heating demand using electric storage heaters (~78%), oil or LPG boilers (~20%) or heat-pumps (~2%).

Retrofit measures

Selected energy efficiency improvements are considered to be applied to the 102 house archetypes in order to investigate the impact of different retrofit solutions on reducing the risk of fuel poverty. For the present study, retrofits are associated with the upgrade of building fabric involving the increase of loft, wall and ground-floor insulation as well as the upgrade of the current heating system. *Table 1* presents the fabric upgrades considered and the case where each retrofit is applied. For example, for a house with solid brick walls where the U-value is greater than 0.60 W/m^{2}K (built before 1983, see *Figure 2*), external insulation is considered to be installed and the new construction should achieve a U_{-value} equal to 0.22 W/m^{2}K. These measures are in line with the recommendations included in SAP Appendix T (SAP, 2014).

Table 1: Retrofit options. Recommendations derived from SAP Appendix T. Derived from SAP (2014).

Retrofit measure	Considered for	Improvement
Loft insulation (R1)	Pitched roof, insulation at joists	Increase insulation to 270 mm
Cavity wall insulation (R2)	Unfilled cavity with U_{-value} > 0.60	Fill cavity
Solid wall insulation (R2)	Brick/Stone walls with U_{-value} > 0.60	External wall insulation U_{-value} = 0.22
Timber wall insulation (R2)	Timber-frame walls with U_{-value} > 0.60	Internal wall insulation U_{-value} = 0.22
Ground-floor insulation (R3)	Insulation <= 50 mm or U_{-value} > 0.50	U_{-value} = 0.18

Regarding the heating system upgrade, houses heated by electric storage heaters or boilers with an efficiency band C (<86%) or below are considered to be retrofitted with a heat-pump. The replacement of the existing heating system with heat-pumps might not be an economically viable solution in terms of capital costs and especially for the case of fuel poor households (unless significant support and incentives are provided by the Government). However, the studied community is not connected to the gas grid and as such, replacing the existing heating system consisting of either electric heaters or old heavy oil boilers with heat-pumps presents significant benefits in terms of running costs (Vatougiou *et al.*, 2020). The present study does not account for installation costs; this should be further investigated in a future work in order to determine whether cost savings are capable of balancing installation costs.

Simulations

The selected loft (R1), wall (R2), ground-floor (R3) and heating system (R4) retrofits are applied both individually and simultaneously. This means that for each house archetype, 4x4 different cases are studied. Python scripts were developed to modify each house archetype using the open source Eppy scripting language (Santosh, 2019). Eppy is written in Python and used to generate the required IDFs. In addition, Python is used to automatically run the simulations, extract the results and perform the analysis. A detailed EnergyPlus Weather (EPW) file for Aberdeen is selected to represent similar climatic conditions with Orkney (EnergyPlus, 2020).

Estimating fuel poverty

Based on the definition of fuel poverty, a household is considered to be fuel poor if its fuel costs *are more than*

10% of the household's adjusted net income. The term "adjusted" is associated with the deduction of housing costs (such as rent or mortgage, council tax and water/sewerage charges), while "net" refers to the income of all adult household members after the deduction of income taxes and national insurance contributions (Scottish Government, 2020a). The Scottish Government publishes national statistics regarding the household's adjusted net income on an annual basis, this being equivalised to the size and composition of the household and provided in decile classes, where the first and ninth decile refers to the poorest tenth and richest tenth of households, respectively. The data for 2018/19 are used in this study to evaluate fuel poverty within the modelled community. The present study does not associate each house archetype with a particular income band. This would require detailed demographic data for each household within the community with the latter being impractical for a fairly large number of houses. Considering this, the paper attempts to evaluate the "sensitivity" of each house archetype (at its current condition and after the application of retrofit scenarios) to be fuel poverty based on different household's income bands.

Results and Discussion

The simulations carried out result in a large volume of outputs containing numerous temperature and energy time-series for the modelled houses and integrated heating systems. *Table 2* shows the mean annual space-heating energy use for house archetypes belonging to nine different categories. The categorization is based on the dwelling's built form (detached, semi-detached, mid-terrace) and external wall U-value (>1.5 W/m^{2}K, =1.0 W/m^{2}K, <0.6 W/m^{2}K). The mean annual energy use of each category is presented for the baseline case (houses at their current condition) and under different retrofit scenarios. The table also shows the mean percentage difference of energy use between the baseline and each retrofit scenario for each category. As shown, the heating energy use for both baseline case and retrofit scenarios generally increases as wall U-value increases and the house becomes "more detached". However, it can be seen that detached houses with U-value lower than 0.6 W/m^{2}K have a mean heating demand greater than those detached houses with U-value equal to 1.0 W/m^{2}K. This can be explained due to the fact that both categories include only 3 houses with this indicating that a strictly statistical comparison of the results is not always possible.

Amongst the different individual fabric retrofit solutions (R1,R2,R3), upgrade of external wall insulation (R2) is found to produce the greatest reduction of the dwelling's energy use; this observation concerns only those houses, which (at their current condition) have wall U-value greater than 0.6 and thus, wall retrofit is an applicable strategy - see *Table 1*). When the three fabric retrofit solutions are applied together as a fabric retrofit package (R1+R2+R3), the reduction of energy use is in in the range of 12.0% - 18.0% for those houses that only loft and floor insulation are applicable measures and in the range of 39.0% - 44.0% when also wall insulation is increased. Heating system retrofit (R4) results in a more significant reduction of the dwelling's energy use compared to any individual fabric retrofit. This happens as for most of the modelled house archetypes, the existing heating system consists of electric heaters (baseline case), which are considered to be retrofitted with an air-source-heat-pump. Nevertheless, it should be clarified that heating system modelling is an ongoing work and is subject to several simplifications at this stage of research. For example, electric storage heaters have been modelled as resistive electric heaters. In actual domestic applications, electric storage heaters do usually use off-peak electricity (e.g. Economy 7 within the UK context) rather than switching ON and OFF based on the house's demand. Therefore, in the present work, energy costs for the baseline scenario are expected to be higher than reality and thus, cost savings resulting from the heat-pump retrofit might be over-estimated.

Table 2: Mean space-heating energy use (in kWh/year) per built form and external wall U-value for baseline and different retrofit scenarios and mean percentage energy use reduction between baseline and retrofit scenarios.

Built form	Wall U-value	Baseline scenario	Individual fabric retrofits			All fabric retrofits	System retrofit	All retrofits
			R1 (loft)	R2 (wall)	R3 (floor)	R1+R2+R3	R4	R1+R2+R3+R4
Detached	> 1.50	**29,363**	26,368 (-10.9%)	22,554 (-22.1%)	28,171 (-4.2%)	17,726 (-39.4%)	21,200 (-30.0%)	13,088 (-56.5%)
	= 1.0	**14,240**	11,773 (-17.1%)	11,569 (-19.1%)	13,336 (-6.3%)	8,041 (-43.5%)	10,425 (-32.5%)	5,974 (-61.1%)
	< 0.6	**16,636**	15,844 (-4.9%)	16,636 (0.0%)	15,290 (-8.3%)	14,471 (-13.4%)	11,309 (-32.0%)	9,779 (-41.3%)
Semi detached	> 1.50	**15,138**	13,836 (-8.6%)	10,584 (-30.7%)	14,619 (-3.3%)	8,404 (45.1%)	10,381 (-32.3%)	6,034 (-61.1%)
	= 1.0	**10,399**	9,307 (-11.0%)	7,979 (-23.2%)	9,908 (-4.8%)	6,285 (-40.1%)	7,001 (-31.4%)	4,375 (-57.4%)
	< 0.6	**7,689**	7,376 (-4.6%)	7,689 (0.0%)	7,190 (-7.4%)	6,878 (-12.0%)	4,494 (-41.6%)	4,011 (-48.6%)
Mid Terrace	> 1.50	**11,645**	10,558 (-9.3%)	8,513 (-26.8%)	11,164 (-4.1%)	6,528 (-43.9%)	7,719 (-33.4%)	4,524 (-60.9%)
	= 1.0	**8,015**	7,019 (-12.9%)	6,564 (-17.8%)	7,548 (-5.9%)	4,928 (-38.9%)	5,096 (-34.5%)	3,258 (-58.5%)
	< 0.6	**4,223**	3,933 (-6.9%)	4,223 (0.0%)	3,780 (-10.5%)	3,463 (-18.0%)	2,453 (-41.9%)	2,066 (-51.1%)

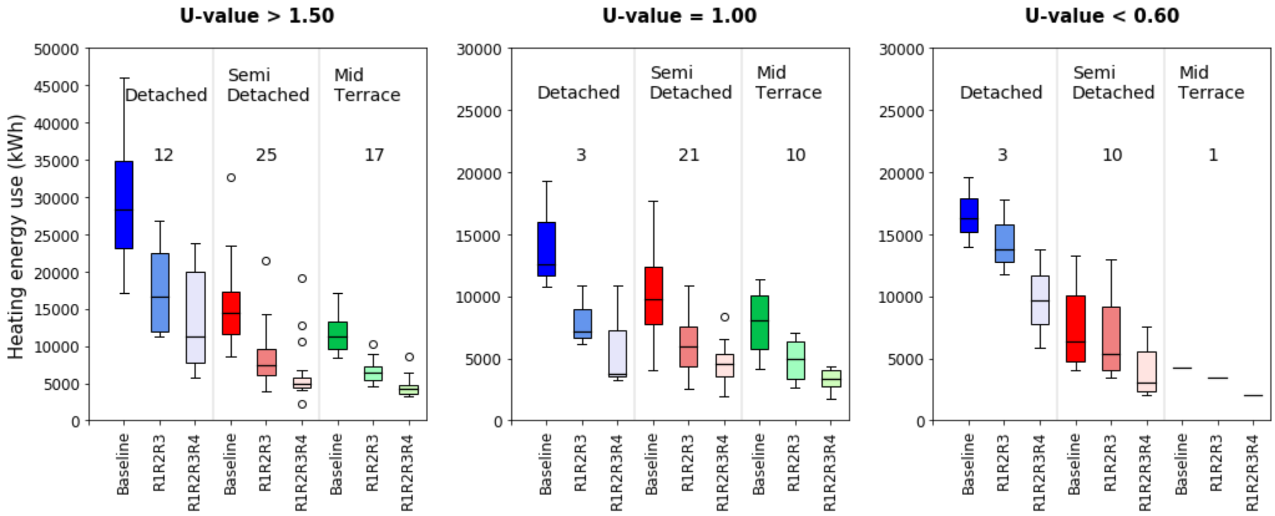

Figure 4: Distribution of the space-heating energy use per external wall insulation level and built form for baseline case and different retrofit scenarios

As expected, a full fabric and heating system retrofit package (R1+R2+R3+R4) appears to be more effective in terms of energy use with energy savings varying from 41.3% to as high as 61.1% between the nine house groups.

Figure 4 illustrates the distribution of the simulated annual space-heating energy use for houses having the same built form and similar external wall U-value for the baseline case and two different retrofit scenarios. The first plot includes all those houses with uninsulated walls while the second and third plot include houses with medium and relatively high wall insulation levels. These distributions are presented in the form of boxplots with the horizontal black line inside each box indicating the median value of the distribution and the black circles depicting outliers[1]. Also, the number of house archetypes included in each distribution are depicted in the figure (e.g. there are 12 house archetypes with baseline wall U-value greater than 1.5 W/m^{2}K). *Figure 4* is a visualization of the simulation results for two of the scenarios included in *Table 2*. This further helps the reader understanding the range of the heating energy use within each category, with this being as high as 20,000 kWh in some cases due to the fact that the house archetypes included in each of the nine categories might present significant variations in size.

Figure 5 illustrates the annual running space-heating costs for each of the 102 modelled house archetypes per external wall U-value and built form. Results are presented for the baseline case (very light colours), "fabric retrofit package" scenario (mid-tone colours) and "fabric retrofit package plus heating system retrofit" scenario (dark colours). Electricity and oil rates are assumed to be £0.1738/kWh and £0.0524/kWh, respectively. The horizontal lines depicted in the figure represent the threshold of annual heating expenses for different household income bands so that households do not spend more than 10% of their income for space-heating costs. For example, a household belonging to the 1st income decile should spent less than £1050.4/year for its energy costs in order to avoid fuel poverty risk. However, the present study considers only space-heating costs, while the 10% definition of fuel poverty refers to the total energy costs of each household with these including hot water, lighting, cooking and other household's appliances. As seen, assuming a scenario, where all house archetypes belong to the lower income band and are at their current condition, only few present annual space-heating costs lower than 10% of their income (24 out of 102). These are mainly some of

Table 3: Percentage of vulnerable to fuel poverty houses within the community for baseline case, full fabric retrofit package and all retrofit scenario (fabric plus heating system). Results are aggregated at the stock level.

Income decile (*10% income*)	**Baseline**	**R2**	**R4**	**R1R2 R3**	**R1R2 R3R4**
1st *(£1050.4)*	46.4	37.6	27.8	21.6	4.2
2nd *(£1440.4)*	36.9	18.0	10.1	8.2	1.3
3rd *(£1747.2)*	20.6	8.5	2.9	5.2	0.3
4th *(£2074.8)*	13.7	5.9	1.3	2.6	0.0
5th *(£2407.6)*	9.5	2.9	1.0	1.3	0.0
6th *(£2745.6)*	5.9	2.6	0.3	1.0	0.0
7th *(£3172)*	2.9	1.4	0.0	0.3	0.0
8th *(£3671.2)*	1.3	0.7	0.0	0.3	0.0
9th *(£4560.4)*	1.0	0.0	0.0	0.0	0.0

[1] Outliers are any values of the distribution found outside the range (Q1-1.5 x IQR) and (Q3+1.5 x IQR), where Q1 and Q3 correspond to the 25th and 75th percentile of the distribution and are represented by the above and below line of each colourful box, respectively. IQR is the difference between Q1 and Q3.

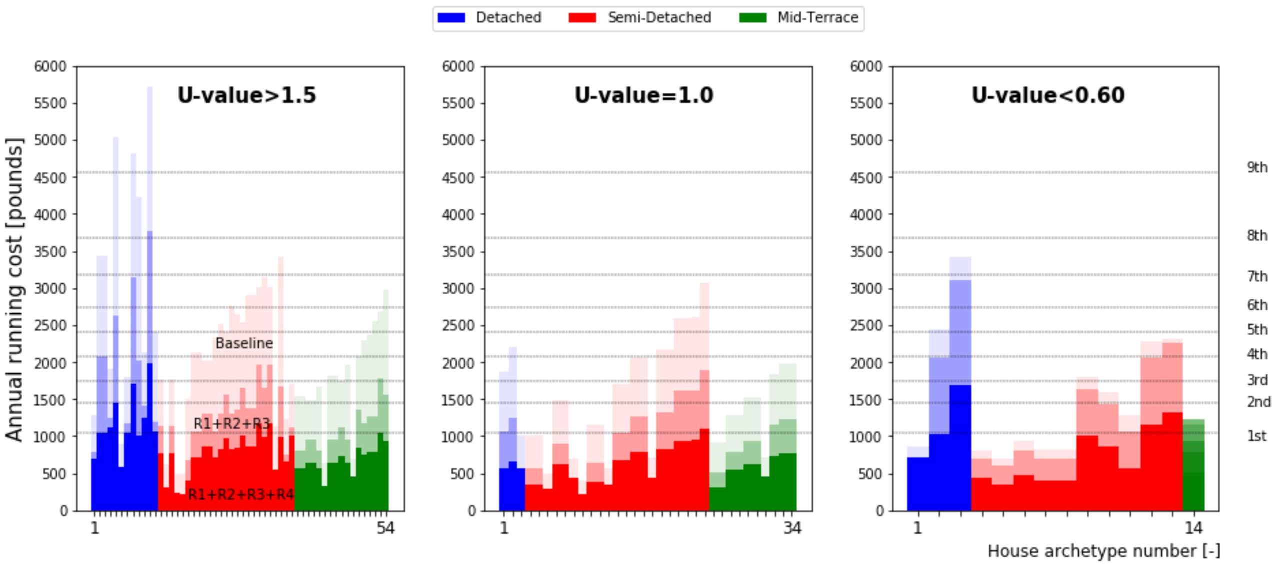

Figure 5: Annual running cost of the modelled house archetypes for baseline case, packaged fabric retrofit scenario (R1+R2+R3) and package fabric plus heating system retrofit scenario (R1+R2+R3+R4)

those houses with medium or relatively high wall insulation levels (U-value=1 and U-value<0.60, respectively)

Table 3 shows the percentage of houses within the modelled community that are found to have annual space-heating costs greater than 10% of different income bands. In this case, the results are aggregated at the stock level; a weighting factor is used for each house archetype corresponding to the number of "real" houses that are represented by this specific archetype. For the baseline scenario, even for households of the highest income band, there are still 3 detached houses with uninsulated walls that are found to be vulnerable to fuel poverty. Retrofit of heating system and wall insulation (when applied as individual measures) limit fuel poverty within the community at the percentage of 28% and 38%, respectively for the case that all houses belong to the lower income band. When the full fabric retrofit package is applied to all houses, the risk of fuel poverty does significantly reduce within the community. However, when all houses are modelled to have income of the bottom and second bottom band, the percentage of vulnerable houses still persists at 21.6% and 8.2%, respectively. Finally, the application of the "all retrofit package" (R1+R2+R3+R4) eliminates fuel poverty risk within the community at a percentage lower than 5% even when all houses are considered to belong to the bottom income band.

Conclusions

The paper evaluates the simulated effect of various retrofit scenarios on the limitation of energy use and fuel poverty risk at the community scale. The annual energy use of 102 house archetypes representing 322 existing dwellings was estimated using the E^+ simulation engine. Houses were studied at their current condition and after the application of individual and multiple retrofit scenarios (including both insulation and heating system upgrades). Simulation results were first presented per various house groups (with each group including houses with similar characteristics) and were then aggregated at the stock level. The sensitivity of each house archetype to fuel poverty risk was assessed based on different income bands for the households. The results suggested that an area-based retrofit scheme can significantly contribute to the elimination of fuel poverty within the studied community. Amongst the individual retrofit measures, upgrade of heating system was found to have the greatest impact on the limitation of fuel poverty followed by wall insulation upgrade. However, heating system energy savings might be lower than the reality as the electric storage heaters were modelled as resistive electric heaters switching ON and OFF based on occupancy. Retrofit of floor and loft insulation resulted in mid-range reductions. When houses were simulated at their current condition, the percentage of houses with space-heating energy costs greater than 10% of their income was found to be 46% for the bottom income band and 1% for the top income band. A full fabric plus heating system retrofit package was found to limit fuel poverty risk below 5% even when all households within the modelled community were considered to belong to the lower income band.

The methodology developed for the present work does not attempt to estimate fuel poverty following Government's approach, but is focused on investigating the effect of different retrofit scenarios on the vulnerability of houses to fuel poverty and the extent to which these retrofits can alleviate the risk of fuel poverty. It is important to highlight again at this point that the study does only account for space-heating demand. Although struggling to meet space-heating demand is the core of fuel poverty issue, it should be noted that the results presented do under-estimate the extent of fuel poverty within the community and hence, they can potentially over-estimate the effect of retrofit on tackling fuel poverty. The results of this work also indicated that even for households belonging to higher income bands, the condition of the house itself can lead to fuel poverty with this indicating that income-based fuel poverty schemes are not always an effective way to target vulnerable houses. Other factors such as the combination of built form and wall insulation level should be evaluated as well (i.e. detached houses with no wall insulation were found to be vulnerable to fuel poverty even for the very high income bands).

Future work should consider different household profiles and controls/tariffs for the modelled heating systems. Finally, it would be of great importance to explore the extent to which these retrofit scenarios also result in carbon savings, this being of particular importance for both Orkney and the entire UK in order to be on truck for its net-zero emissions commitment.

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