Evaluating Cost-effective Retrofit at the Community Scale; the Case of Orkney Islands

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Abstract

This work focuses on evaluating the economic viability of different Energy Efficiency Measures (EEMS) in a grid-constrained community (some 320 dwellings) using a bottom-up housing stock energy model integrated with dynamic thermal simulations. Deriving information from Energy Performance Certificates (EPC) (or equivalent data sets) and accessing GIS (relating to geometry) data, the model automatically implements an archetyping process and creates EnergyPlus house models. Based on the current condition of the derived house archetypes, a series of EEMS (both fabric and heating system upgrades) are modelled and evaluated at the archetype-level as well as at the stock-level using economic indicators (payback period and net present value). The application of cost-effective EEMS resulted in 57% energy savings across the modelled community. The payback periods are found to be as low as 3.3 and 6.5 years for cavity-wall and loft insulation upgrades as high as 20.1 and 21.3 years for external-wall and floor insulation upgrades, respectively. Replacement of conventional heating systems with heat-pumps results in payback period of 12 years on average.

Introduction

Increasing the energy efficiency of the existing building stock is recognized by BEIS (Department of Business, Energy & Industrial Strategy) and CCC (Committee on Climate Change) not only as a necessity if the UK Government’s commitment to net zero emissions is to be met by 2050, but also as the most cost-effective way to achieve it (CCC, 2019). Based on provisional figures for 2019, UK residential buildings account for 19% of all national carbon dioxide emissions, reflecting a decrease of 17% from 1990 levels (BEIS, 2020). The introduction of new building regulations ensure that new houses are now built at higher energy standards. However, a deep national decarbonization of the existing housing stock (~29 million) is a critical part of the UK’s net zero emissions pathway. This is of particular importance considering that around 80% of houses that will exist in 2050 have already been built.

In an effort to address the need for a decarbonized housing stock as well as alleviate fuel poverty, the UK Government has rolled-out different incentives providing income to households to adopt EEMS. However, a recent report of the CCC mentions that previous legislative schemes such as the Green Deal and Renewable Heat Incentive have significantly under-performed to the government’s initial expectations (CCC, 2019b). Even those relatively “easy-to-apply” EEMS such as cavity-wall and loft insulation were not delivered adequately. In addition to that, shifting homes away from natural gas has proved to be very challenging during the last decade. Currently, less than 200,000 UK homes use heat pumps as their main heating source (CCC, 2019b) making the UK heat pump market one of the least developed across Europe.

The recent commitment of the UK Government to phase out the installation of fossil fuel-based heating systems to new-built houses is expected to stimulate an increase of electrified heating systems in the market. Considering that renewables’ share to electricity generation has reached 47% in the first quarter of 2020 (BEIS, 2020b), a large-scale electrification of domestic heating is one of the most promising scenarios to decarbonize heat (followed by the conversion of the gas grid to hydrogen). However, questions still exist around how the existing housing stock will be made energy efficient. The main challenge that policy should tackle is disruption to consumers, e.g., how consumers are expected to respond to the need for more expensive heating systems (Whinskel et al., 2019). In this context, policy has a twofold role; to increase the currently low public awareness about the “low-carbon living” concept; and to support the roll-out of beneficial incentives for consumers to undertake suitable EEMS. In this context, the wide adoption of low-carbon heating solutions should undeniably be in the centre of future EEM schemes. Nevertheless, in order for technologies such as heat pumps to be a techno-economically viable solution across the range of housing stock (maintaining comfort and ensuring cost benefits for consumers), the fabric condition of most UK dwellings should be substantially upgraded (Lingard, 2020).

Cost-effectiveness of EEMS

The UK Government’s Standard Assessment Procedure (SAP) (Appendix T) includes a list of all EEMS to be considered based on the dwelling’s current condition (SAP, 2014). These involve upgrading wall, loft and floor insulation, improving air tightness through the application of draughtproofing measures, increasing efficiency of heating systems and reducing electricity consumption through energy management systems. However, considering that resources are usually limited either at the individual-building level or within the context of area-
based energy efficiency schemes, EEMs cannot be applied at once, thus establishing ranking criteria to proceed with investments is important (OberEGGER et al., 2020). Both the selection of the EEMs to be applied and buildings to be refurbished is a multi-objective decision-making process including factors such as available budget, renovation rate, project targets (e.g., anticipated energy savings, emission reduction targets), consumers’ profile, etc. Combining several of these factors, a cost-effective methodology should a vital part of retrofit projects allowing consumers to see the real benefit before making an investment decision.

Generally speaking, the core of a cost-effective methodological approach is to assess total costs and benefits associated with a specific investment, this (for the case of retrofit) involving the comparison of the cost required to install (and maintain) an EEM against the amount of fuel saved over its technical lifetime. Based on that, an investment is considered to be economically-viable if the total amount of running cost savings as a result of a retrofit solution is greater than its total capital (and maintenance) cost (Shaikh et al., 2017). Previous works have used a variety of different indicators to evaluate the cost-effectiveness of EEMs such as simple or discounted payback period, net present value, internal rate of return, life cycle cost, levelized cost of saved energy.

Urban building energy modelling

Using building performance simulations to investigate the impact of EEMs on the heating performance of individual buildings is a well-documented research area (Marshall et al., 2016). The increasing need to explore suitable pathways towards low energy consumption and reduced carbon emissions across the range of UK dwellings has brought housing stock models in the current interest of literature. 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 investigate the impact of large-scale retrofit projects in Wales. He et al. (2015) developed a dynamic housing stock model to identify cost-effective combinations of various fabric EEMs using a multi-objective optimization method. The model was applied to some 800 archetypes representing a large part of the housing stock of the North-East region of England and the prioritization of EEMs to be applied and houses to be retrofitted was explored under different available retrofit budgets. Gupta and Gregg (2018) developed a GIS-based model to assess the effectiveness of a wide range of retrofit measures (applied both individually and as retrofit packages) for a neighbourhood in Bicester, UK following a house-by-house modelling approach and using SAP calculations. The authors employed payback period to evaluate the cost-effectiveness of the modelled EEMs assuming that an intervention is financially profitable if its associated payback period is less than the intervention’s lifetime. Their analysis showed that the adoption of heat-pumps resulted in significant payback periods that do not justify the investment. OberEGGER et al., (2020) developed a methodology to prioritize EEMs at the housing stock level based on the LCSE (in euro per saved kWh) and given that retrofit budgets are fixed. Their methodology allowed for the definition of numerous steps showing the buildings to be retrofitted across the stock, EEMs to be applied, retrofit costs and anticipated energy savings. The authors applied the developed methodology for a case study area in northern Italy and the results were communicated using an energy efficiency cost curve allowing for policymakers to identify initial investment required to achieve different energy saving targets. The results showed that the EEMs with the lowest LCSE is wall insulation followed by roof insulation, while the LCSE for basement ceiling insulation and window replacement depends on house type. A similar approach was presented by Streicher et al. (2017) for the Swiss housing stock.

Objectives

When it comes to retrofit, off-gas regions are found at the centre of debate due to their limited access to alternative heating options and constraints they often experience to change fuel supplier. On the other hand, in these areas, the ground might be more “prepared” for the large-scale penetration of high-capital-cost technologies such as heat-pumps due to the significantly higher running costs of conventional electrified heating systems found in a large number of houses. In economic terms, heat-pumps can more effectively compete with conventional resistive heaters, storage heaters or even oil-fired boilers than gas boilers, with the latter not only being a “well-trusted” technology within the UK context, but also using a considerably lower-price fuel (electricity to gas price ratio per kWh ~ 4).

Using a thermal stock model and employing well-established economic indicators, this work assesses the cost-effectiveness of different retrofit scenarios applied to a grid-constrained community, the scenarios ranging from “shallow” individual measures to “deep” whole house interventions. The objective of this paper is to estimate the impact of retrofit options on the aggregated heating demand, explore the different relative impact depending on house characteristics and identify the extent to which EEMs (applied either individually or combined) are economically viable solutions across the range of the stock.

Methodology

The following sections focus on providing a description of the case study area, the methods followed to model and estimate the heating demand of the selected housing stock, the fabric and heating-system retrofit solutions considered with their associated costs and the economic indicators used to assess cost-effectiveness of retrofit scenarios.

Case study area

A community of 322 dwellings is used as the test case for the purposes of the present study. These houses compose a unique data zone (S01011824) located in East Kirkwall, Orkney, Scotland (Figure 1, orange houses). Data zones are aggregates of Census Output Areas designed to represent communities of 500-1000 residents (data zones
are designed to be large enough so that statistics can be well represented).

Orkney Islands are located in the North-East of Scotland accommodating the highest concentration of wind turbines in the UK supplemented by solar, wave and tidal energy. The islands currently produce more than 100% of their own electricity needs. Nevertheless, lacking connectivity with the mainland, generators cannot export their surplus, with this resulting in significant RES curtailments. The creation of a flexible local energy system integrating power, heat and transport is of current importance for the islands. For the building stock, in particular, a large-scale deployment of heat-pumps is expected to significantly contribute to a 100% renewable future on the islands and as such, it should be encouraged with suitable financial incentives for consumers. Considering that Orkney present one of the highest percentages of fuel poverty across Scotland (Orkney Islands Council, 2017), the latter should be seriously taken into account and prioritized by policy.

Housing stock modelling

The selected houses are modelled using a parametric housing stock thermal model (McCallum et al., 2020) capturing geometric and other physical house properties to implement an archetyping process and automatically generate EnergyPlus Input Data Files (.idf). Based on the current version of the model, six dimensional parameters are accessed through GIS-relating to geometry data (Open Street Map) including dwelling’s width, depth, height, T-shape projection, T-shape offset-left and T-shape offset-right. Another five parameters (number of storeys, SAP age band, exterior wall construction type, adjacencies, heating system type) are captured for the archetyping process using EPC and HA data sets. It should be noted here that HA are available within the Scottish context and contain data from various data sets such as EPCs, HEED (Home Energy Efficiency Database), Scottish Census, etc. (EST, 2021). It should be noted that EPC and HA data were accessed due to links with the Orkney Islands Council (OIC). For the case of the present study, the selected community (322 houses) is represented by some 100 unique house archetypes; the number of “real” houses being represented by each archetype varies from 1 to 20 (weightings). Figure 2 illustrates the composition of the modelled housing stock.

For each archetype, the combination of dwelling’s age band and exterior wall construction is then used as an indicator to determine exterior wall U-value based on Table S7 of RdSAP (Reduced Data Standard Assessment Procedure). In a similar way, RdSAP Table S10 and Table S11 are used to assign upper-ceiling insulation thickness and ground-floor construction, respectively (SAP, 2016). At their current state, houses meet their space-heating demand using electric storage or resistive heaters (~80%), oil or LPG boilers (~20%) and heat-pumps (~2%).

Modelling limitations:

The parametric thermal stock model used in this work to generate the studied house archetypes is a result of an ongoing work. At this stage, house archetype models are subject to several imputations and simplifications, these being summarized as follows:

- In the archetyping process, SAP age bands (as accessed form EPC registers) are grouped in the same manner as in HA; A (pre-1919), BC (1919-1949), DEF (1950-1983), G (1984-1991) and HI (1992-2002), JL (post-2012). Nevertheless, grouping together age bands DEF does not allow for the significant difference in U-values between age bands DE and F to be captured, this resulting from the introduction of 1976 Building Regulations that imposed (for the first time) significant limitations to exterior-wall U-values. As seen in Table 1, the U-value modelled for archetypes belonging to DEF group is that corresponding to age band D (based on RdSAP Table S7). This is expected to under-estimate the condition of the stock. Future versions of the model will address this issue.

- Each floor is modelled to be a unique thermal zone. Future plans include the definition of room-specific thermal zones, which will allow
for the variation of heating and occupancy patterns to be modelled.

- All houses are considered to have double-glazed windows, equally distributed to dwelling’s facades covering 25% of external wall area.
- An infiltration rate of 0.6 ACH is modelled for all archetypes. To allow for variation in infiltration across the stock, future work will consider infiltration rates depending on the dwelling’s number of storeys, type of wall and floor construction, type of windows, etc. as recommended by SAP.
- Most houses archetypes (~80%) have either electric resistive heaters or electric storage heaters. Within Orkney context, most houses with storage heaters use the Total Heating Total Control (THTC) tariff provided by SSE. This is controlled by radio signals and offers lower rates around 5-12 hours/day, thus allowing storage heaters to receive top-ups during the day (unlike to the conventional UK Economy-7 tariff). Future work aims to analyse smart meter monitors to understand the operation patterns of storage heaters and create representative EnergyPlus models. In this work, storage heaters are modelled as resistive electric heaters switching on and off based on house’s demand acknowledging that this might result in over-estimation of the total energy use.

### Fabric and heating system EEMs

The EEMs applied to the baseline house archetypes include insulation upgrade for upper-ceiling/loft construction (R1), exterior walls (R2), ground-floor (R3) as well as heating system upgrade (R4). These are applied both individually and as combined measures based on the archetype’s current condition. More specifically, for each unique archetype, a maximum of 15 simulations are performed including the application of four single EEMs, six combinations of two EEMs, four combinations of three EEMs and one combination of all EEMs

**Fabric**

*Table 1* includes the different fabric improvements considered for the purposes of this study as recommended by SAP-Appendix T. External Wall Insulation (EWI) is considered for solid brick and non-traditional walls built with a systemized process (referred as system-built), Cavity Wall Insulation (CWI) for un-filled cavity walls and Internal Wall Insulation (IWI) for timber-framed walls. For the case of system-built wall constructions, EWI is used as the cavity (if exists) is usually narrow for insulation to be effectively injected. As seen in the table, all those houses with current wall U-value lower than 0.6 W/m²K (age band F or lower) are considered to be eligible for wall insulation upgrade. Regarding loft construction, SAP recommends that insulation should be upgraded to 270mm in all those houses with current insulation thickness lower than 150mm. For the case of ground-floors, retrofit is considered if current U-value is lower than 0.50 W/m²K (SAP, 2014).

### Heating system

An Air-to-Water-Heat-Pump (AWHP) coupled with a 300L storage heater tank is considered to be retrofitted in those houses with electric heaters (either storage or resistive) or boilers of category lower than B. The AWHP operates based on the dynamic Time-of-Use (ToU) Agile tariff, this providing sub-hourly price signals throughout the day. The electricity rates for 2020 are illustrated in Figure 3 and used in this work to calculate annual running space-heating costs (Octopus Energy, 2021). As seen, prices for this tariff are higher than that of a conventional flat tariff (shown with the horizontal black line) between 4-7 pm (from November to March) or between 3-6 pm (for the rest of the year). The AWHP is controlled to perform a 3-hour pre-heating of the storage tank to eliminate the system’s operation during high-tariff periods. The AWHP model with the associated control strategy is described in Vatougiu et al. (2020).

![Figure 3: Agile tariff, daily electricity rates for 2020 (Octopus Energy, 2020)](attachment:figure3.png)

To model EEMs, 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 IDF files. 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.

### Capital cost of EEMs

The cost of retrofit ($I_W$) is estimated using *Equation (1)* as follows:

$$I_W = \sum_i (A_{W_i} \times C_{W_{insi}}) + \sum_i (A_{L_i} \times C_{L_{insi}}) + \sum_i (A_{F_i} \times C_{F_{insi}}) + C_{HVAC} \text{ (in £)} \quad (1),$$

where:

- $A_{W_i}, A_{L_i}, A_{F_i}$ is the total exterior-wall, loft and ground-floor area in m², $C_{W_{insi}}, C_{L_{insi}}, C_{F_{insi}}$ is the cost of wall, loft and floor insulation per each element’s area in £/m² including material and labour costs and $C_{HVAC}$ is the cost of the heating system replacement including capital and installation costs. *Table 2* provides indicative retrofit costs for the various interventions including material and labour costs. The data included in this table are derived

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600
undertaken at scale. Installation costs for a typical domestic heat pump system including fittings, buffer tank, as heating system replacement are not usually found to be around £10,500 (BEIS, 2018).

As noted in this source, a discount of capital retrofit costs (BEIS, 2017) and resulted from a number of interviews with installers, contractors, manufacturers, etc. As noted in this source, a discount of capital retrofit costs is usually applied in the case of mass retrofit installations due to reduced labour and transport costs (economies of scale). However, ground-floor insulation upgrade as well as heating system replacement are not EEMs usually undertaken at scale. Installation costs for a typical domestic heat pump system including fittings, buffer tank, water cylinder and controls (without retrofitting heat distribution system) are found to be around £10,500 (BEIS, 2018).

Table 2: Indicative costs per retrofitted area. Source: BEIS (excluding VAT) (2017)

<table>
<thead>
<tr>
<th>EEM</th>
<th>Cost per retrofitted area (£/m²)</th>
<th>Discount</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lowest</td>
<td>Median</td>
</tr>
<tr>
<td>EW1</td>
<td>55</td>
<td>95</td>
</tr>
<tr>
<td>IWI</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>CW1</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Loft</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Ground-floor</td>
<td>£1/m²</td>
<td>+£500-£600</td>
</tr>
</tbody>
</table>

Cost-effectiveness of EEMs

The indicators used to assess the economic viability of EEMs is Net Present Value (NPV), Simple Payback Period (SPP) and Discount Payback Period (DPP). SPP is calculated as the ratio of the total cost associated with the installation of a retrofit measure to the annual reduction of running costs as compared with pre-retrofit condition. Unlike SPP (which considers a static reduction of annual running costs), DPP and NPV accounts for the time value of money. More specifically, NPV is estimated using Equation (2) and aims to estimate the total amount of money that can be gained over an investment’s lifetime. In a similar manner, DPP results from Equation (3).

\[
NPV = \sum_{t=0}^{n} \frac{(CI-CO)_{t}}{(1+i)^t} \quad (2)
\]

\[
\sum_{t=1}^{n} \frac{(CI-CO)}{(1+r)^t} = CI_{t} \quad (3),
\]

where:

- \( i \) is the discount rate, \( (CI-CO) \) is the cash-flow per year with \( CI \) and \( CO \) representing annual cost inputs (i.e., difference of annual running costs from pre-retrofit condition) and outputs (i.e., investment cost), respectively and \( n \) is the investment’s lifetime. Within the UK context, a discount rate of 3.5% is indicative for residential retrofit applications (Ofgem). The lifetime of the different fabric and heating system EEMs is considered to be equal to 30 years, while maintenance and operating costs are ignored.

Results and Discussion

Heating energy use

Figure 4 (a) illustrates the annual predicted space-heating energy use of the modelled house archetypes for the baseline scenario (pre-retrofit) and after the application of different fabric EEMs. As seen, archetypes are grouped based on built form (detached, semi-detached and mid-terrace represented by blue, red and green colour, respectively). Different tones of these colours are used to illustrate the reduction of the baseline energy use as a result of individual EEMs including loft insulation upgrade (R1) and wall insulation upgrade (R2) as well as a combined EEM consisting of loft/wall/ground-floor insulation upgrade (R1+R2+R3). The upgrade of ground-floor insulation is found to have an almost negligible impact on the dwelling’s demand. As seen in Table 3 (presenting the effect of individual EEMs at the stock-level), the total demand reduction as a result of ground-floor insulation (when applied across the entire stock) is only 1.7%. In a similar manner, Figure 4 (b) illustrates the reduction of each archetype’s energy use resulting from heating system upgrade (R4: mid-toned colours) and whole-house retrofit including a combined fabric improvement plus heating system upgrade scenario (R1+R2+R3+R4: darker colours).

Amongst the individual EEMs, heating system upgrade is found to achieve the highest reduction of baseline energy use (48.5%), this being even higher than the reduction achieved through the consideration of the combined fabric EEMs (R1+R2+R3). The reason for that is the replacement of conventional electric heating systems found in almost 80% of the modelled house archetypes with AWHPs.
Table 3 shows the aggregated reduction of energy use across the stock as a result of the retrofit scenarios included in the above figures. In this case, measures are considered to be applied without accounting for their economic viability (i.e., cost-effectiveness is not an objective for selected whether or not to proceed with an investment) and a fabric improvement plus heating system upgrade scenario results in 68% energy savings at the community-level.

Table 3: Aggregated retrofit cost and space-heating demand reduction from baseline scenario for individual EEMs

<table>
<thead>
<tr>
<th>EEM</th>
<th>Total retrofit cost (£)</th>
<th>Total demand reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>108,461</td>
<td>9.5</td>
</tr>
<tr>
<td>R2</td>
<td>981,502</td>
<td>22.6</td>
</tr>
<tr>
<td>R3</td>
<td>116,016</td>
<td>1.7</td>
</tr>
<tr>
<td>R4</td>
<td>1,450,000</td>
<td>48.5</td>
</tr>
<tr>
<td>R1R2R3</td>
<td>1,205,979</td>
<td>37.1</td>
</tr>
<tr>
<td>R1R2R3R4</td>
<td>2,610,979</td>
<td>68.04</td>
</tr>
</tbody>
</table>

1 Median costs per retrofitted area (see Table 2)

Economic viability of retrofit scenarios

Figure 5 illustrates the distribution of NPV per built form and under different EEMs; due to the significant variation of investment cost involved around the different wall retrofit techniques, EWI, CWI and IWI measures are shown separately. The NPVs included in the figure were estimated using median investment costs as shown in Table 2. 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 (i.e., points outside the range $Q_1-1.5*(Q_3-Q_1)$ to $(Q_3+1.5*(Q_3-Q_1))$, where $Q_1$ and $Q_3$ correspond to the 25th and 75th percentile of the distribution, respectively). The number of total archetypes included in each group is annotated below each box, while the number of houses per distribution that were found to be eligible for each EEM in terms of NPV is annotated with blue colour above each box. In this case, an investment is considered to be economically viable if NPV is greater than 0. Although the application of IWI is a less expensive EEM compared to EWI, IWI is found to be financially impractical for all the modelled archetypes. This could be explained by the fact that the original U-value (baseline scenario) of houses considered to be retrofitted with EWI (solid and system-built constructions with U-values equal to 1.7 W/m²K and 2 W/m²K, respectively) might be significantly higher than that of houses undertaking IWI as an EEM. More specifically, most houses with timber-framed wall constructions belong to DEF age bands and were modelled with a U-value equal to 1 W/m²K resulting in lower running cost savings throughout the investment’s lifetime compared to houses with solid and system-built wall constructions. However, due to the very limited number of archetypes included in some groups (e.g., only 3 detached houses undertake EWI and IWI), a strict statistical comparison between the different groups might not be representative as the size of houses included in each category could be an influential factor.

Figure 6 illustrates the impact of initial retrofit costs on NPV with the very light, mid-toned and dark colours corresponding to the lowest, median and highest cost per retrofitted area, respectively as included in Table 2. Based on that, the application of IWI becomes a profitable EEM for all the modelled archetypes when the lowest price per
The retrofitted area is considered and EWI is not economically viable under the highest price scenario (excluding few mid-terraced houses).

**Figure 6:** Net Present Value for exterior-wall insulation upgrade under different initial investment costs

**Figure 7 (a) and (b)** illustrate the distribution of SPP and DPP for the different built forms and individual EEMs applied. Boxplots contain only those archetypes for which the application of each EEM results in paybacks lower than 30 years (investment’s lifetime). As expected, DPP is generally higher than SPP. In addition to that, when using the SPP as an indicator, more EEM investments are found to be economically feasible across the stock. For example, none of the archetypes is found to be eligible for IW1 when using DPP, while 26 out of the 33 archetypes undertaking IW1 achieve SPP lower than 30 years.

**Table 4:** Economically-viable combinations of EEMs based on DPP

<table>
<thead>
<tr>
<th>EEM(s)</th>
<th>No of archetypes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loft upgrade (R1)</td>
<td>18</td>
</tr>
<tr>
<td>Combined loft &amp; wall upgrade</td>
<td>8</td>
</tr>
<tr>
<td>Combined loft &amp; floor upgrade</td>
<td>5</td>
</tr>
<tr>
<td>Combined loft &amp; HVAC upgrade</td>
<td>11</td>
</tr>
<tr>
<td>Combined wall &amp; HVAC upgrade</td>
<td>1</td>
</tr>
<tr>
<td>Combined loft &amp; wall &amp; HVAC upgrade</td>
<td>28</td>
</tr>
<tr>
<td>Combined loft &amp; floor &amp; HVAC upgrade</td>
<td>19</td>
</tr>
<tr>
<td>All EEMs (R1+R2+R3+R4)</td>
<td>11</td>
</tr>
</tbody>
</table>

**Conclusions**

This work used a grid-constrained community as the case study area to investigate the economic viability of fabric and heating system EEMs applied both individually and as combined measures. Using a parametric thermal stock model integrated with dynamic building simulations, 322 houses were modelled based on an automated archetyping process and their space-heating energy demand was estimated throughout the winter heating months for both pre- and post-retrofit scenarios. The cost-effectiveness of the applied EEMs was determined using recognized economic indicators and the results showed that if all cost-effective measures are applied to the studied community, the aggregated predicted heating energy use can be reduced up to 58%. However, evidence exists that the actual financial benefit resulting from the applications of EEMs to existing dwellings is less than predicted (rebound effect). This could be more evident for the case of low-income and fuel poor households, where energy savings from EEMs are often taken as increased comfort (Milne and Boardman, 2000).

Current EPCs, using SAP (or RdSAP) steady-state calculation methodology, provide recommendations for energy efficiency improvements based on the current condition of dwellings and cost-effective criteria. Although the intention of EPCs is to encourage the deployment of low-carbon heating technologies, they underestimate both their environmental and financial benefits. On the environmental side, SAP currently uses an outdated figure of CO₂/kWh of electricity resulting in poor ratings for electrified heating systems such as heat pumps. Although this is subject to change in following SAP versions, the utilization of static figures is problematic by itself. In addition to that, the use of conventional flat tariffs (which is the case within EPC context) as opposed to dynamic ToU tariffs, does not allow for the real economic benefit of low-carbon heating to be revealed making technologies such as heat-pumps to be financially unattractive in the eyes of investors.
(Carmichael et al., 2020). Given the rapid decarbonisation of the power sector and the significant daily and seasonal variation of renewables’ share on electricity generation, the utilization of models that are capable of integrating demand-side management strategies and dealing with the fluctuations of electricity carbon intensity on the grid is of particular importance.

The limitations of the thermal stock model used in this work to study the selected community were summarized in the methodology section of this paper. A significant part of our ongoing work involves the use of smart meter records to validate the parametric thermal stock model and improve heating system modelling. The work presented in this paper is part of a consortium effort to convert Orkney into a carbon-free region and future applications will focus on larger-scale areas.

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References