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LCRI Convergence Cross Cutting Themes

Scenario Modelling for a Low Carbon Wales

Regional scale modelling on the potential for CO_2 emission and cost savings by low carbon measures in the Welsh domestic sector

Retrofit 2050 Working paper

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1 INTRODUCTION

The Welsh Government have declared a strong commitment to achieve annual carbon equivalent emissions reductions of 3% per year in areas of devolved competence, relating to all direct GHG emissions in Wales not covered by the EU ETS. In addition, power generation emissions (for the most part covered by EU ETS) are also included in the 3% target, by assigning them to the end-user in each of the non-traded sectors [1]. By this definition, the residential sector represents 30% of the emissions within Welsh Government competence and becomes one of the key areas of intervention where potential large savings could be achieved towards the policy targets within devolved competence by 2020 [1, 2].

Housing is an area of devolved responsibility, with the Welsh Government and 22 Welsh Local Authorities being jointly active in retrofitting the housing stock. Local councils are responsible for upgrading the stock that fails, maintaining the standard over the following years [3] and ensuring sustainable development within their boundaries by identifying and supporting sustainable and viable renewable energy schemes [4].

The Welsh residential sector has a larger share of hard to treat properties[1] compared to the rest of the UK, which indicates large scope for improvement in energy efficiency but potentially also larger associated marginal costs [5]. Whilst a wide range of potential retrofit measures are available, the main technical means of reducing energy consumption and carbon dioxide emissions from existing dwellings in Wales fall into three broad categories: (i) changing the energy source for space and water heating to more carbon and energy efficient alternatives; (ii) insulation and improvements to air tightness; and (iii) the use of small scale renewable energy systems at the local level [2].

Despite a number of studies at UK level, there is limited research into the disaggregated potential for energy, carbon and cost savings achievable by readily available energy efficiency and low carbon measures in the Welsh local authorities.

This paper presents the results of an effort to estimate potential, CO_2 emission reduction and monetary benefits from the retrofit of low carbon measures in each of the local authorities in Wales using regional data to account for stock-specific constraints in each locality. The work is based on the methodology used to model the domestic sector in the Centre for Low Carbon Future's recent report "The Economics of Low Carbon Cities" [6]. The paper is structured as follows: section 2 gives a short review of residential models in the context of Wales; section 3 briefly describes the methodology of the residential model employed; section 4 contains the compositional downscale data relevant to the Welsh local authorities; section 5 presents results for local authorities in Wales for selected scenarios; and finally a discussion of limitations and future work is given is section 6.

2 MODELLING THE RESIDENTIAL SECTOR

Residential energy consumption is influenced by many parameters, and thus the evaluation of the effectiveness of policies and intervention scenarios is not a simple task. Previous work

[1] Hard to treat properties have solid walls and are off the gas network. Solid wall properties account for 37% of the total in Wales and 27% in England. The proportion of properties off the gas network is 37% in Wales against 15% in England.

on policy options for the reduction of GHG emissions in Wales [2] has concluded that it is difficult to predict the impacts of policy measures in the long term, because of the uncertainty over many of the variables involved. This is not a Wales specific observation; wider literature stresses the important that such efforts are supported by appropriate methodologies, as these complex questions can only be addressed through detailed mathematical models, which can calculate the energy demand based on specific input parameters [7-9].

The majority of literature divides modelling methods in two categories: top-down models and bottom-up models [9]. Top-down models are based on regression analysis in order to examine the relationship between energy consumption and demographic, financial and technological factors. Bottom-up models are based on the examination of a sample of individual houses and then extrapolate the result to a regional or a national level [10]. One of the most important limitations of the models is the lack of appropriate input data or absence of data in general [10], as well as the level of disaggregation of input data. Both types of models can provide relatively robust results given the right configuration; bottom up approaches examine scenarios providing a great level of disaggregation and detail, including new technological features, but require significant input; top-down models usually rely on historical data in order to derive robust results.

A number of residential models have been developed as policy support tools, providing projections at the national level [11-17]. The majority of these [12-16] are based on the BREDEM tool, which has a great level of complexity and, consequently, requires a lot of input from several data sources for its application [13]. Despite a number of studies at UK level, there is limited research into the disaggregated potential for energy, carbon and cost savings achievable by readily available energy efficiency and low carbon measures in the Welsh local authorities. Examining the application of these models in the context of the Welsh local authorities [18, 19] reveals a number of issues with lack of data [13]; the interpolation and substitution of data based on other regions [15, 16, 20]; and the aggregated nature of results [14] limiting the potential for regional insights. At the time of writing there is no representative residential stock model for Wales.

In contrast the models developed in a Wales specific context [21-24] consist of bottom-up applications that have initially been demonstrated by modelling specific local authorities. These modelling efforts have been effective in representing these sub-regional areas but their reliability depends on detailed housing stock statistical surveys and therefore it is difficult to extend their application to the rest of the local authorities, although there are ongoing efforts to that extent.

The model used in the work presented here - referred to as the Low Carbon Regions (LCR) model - is a top-down model, using data from the UK Committee on Climate Change (CCC) on the potential energy, cost and carbon savings from a range of low carbon measures, at the same time considering changes in the fuel costs and energy mix [6]. While in essence the sector specific data is still derived through the application of BREDEM this is done through the use of a single "average" type of home and therefore requires less detailed input data [25, 26]. By customising the level and detail of input provided the model has the ability to offer the potential energy, cost and carbon savings from a range of low carbon measures downscaled at local authority level by taking into consideration region-specific housing stock information. More information on the LCR model is given in the following section.

3 MODELLING METHODOLOGY

3.1 Background

The LCR domestic model is based on CCC data that was developed to assess the potential energy, cost and carbon savings for a variety of low carbon measures in the residential sector, over and above a baseline scenario, which are theoretically possible at the UK level, and subsequent work to reduce that potential to what can realistically be achieved under certain conditions [25-28].

The work on Marginal Abatement Cost (MAC) Curves for the domestic sector was produced by BRE through the use of detailed models, where an S shaped curve formed partly on past trends and partly on future predictions is applied to each technology to generate measure uptake [25]. The MAC curves are used to examine costs in isolation with the purpose of ranking measures, or calculate savings from a particular measure accounting for interactions by assuming that all other relevant measures have been applied. Both methods provide minimum estimates of the savings achievable [26]. Additionally, the effect of prioritising the installation of measures differently has been found to be small in relation to the uncertainty in the energy saving figures, considering that corrections are already applied to account for the occupants' comfort factor and reduced in-situ performance [25].

Updates of the work [27, 28] acknowledge the importance of timescales for delivery of the potential identified in the MAC curves, as well as demand and supply chain constraints such as availability of raw materials, qualified installers, credit flow and capability for scaling up production and the ability to identify appropriate customers, which was considered a key barrier. It also looked further interaction between different types of measures, and the decision process with regards to the uptake of energy efficiency in buildings, in respect of the number of people coming forward to adopt a measure in a given year and how that may be affected by hidden costs, which may alter the decision makers' willingness to pay.

The LCR model uses data from the CCC work described in the above to reflect the cost of adopting one unit of each measure and the energy (and hence the financial and carbon) savings that can be expected annually and over the lifetime of that measure. The costs considered include the capital costs, running costs and any hidden or missing costs (i.e. the costs of searching for or adopting the measure). Throughout the analysis, realistic projections of the energy, cost and carbon savings emerging from different measures are adopted. The estimates of energy savings used are conservative and take into account implementation gaps and rebound effects. Furthermore the scope for the adoption of different measures is adjusted to take into account hard to reach households. The data includes a list of energy efficiency measures (both technological and behavioural) and small-scale renewable technologies that are already available and have significant potential for future adoption. This list of measures is not complete - however it is the most detailed and extensive list available that is underpinned by robust and broadly comparable data sets. Out of these measures a number were selected for this study, as shown in Table 1. Renewable generation measures have not been included in the study at this stage due to lack of reliable data. Although it would be of interest to include small scale renewables, note that the uptake curves produced for renewable generation show that the effect would not be significant for the first three carbon budgets [25].

Table 1: Selection of measures included in the present study

Fabric measures	Wall Insulation	Pre76 cavity wall insulation
		76-83 cavity wall insulation
		Post '83 cavity wall insulation
		Solid wall insulation
		Paper type solid wall insulation
	Loft Insulation	Loft insulation 0 - 270mm
		Loft insulation 25 - 270mm
		Loft insulation 50 - 270mm
		Loft insulation 75 - 270mm
		Loft insulation 100 - 270mm
	Glazing	Glazing - single to new
		Glazing - old double to new double
		Glazing (to Best Practice)
	Other	Improve airtightness
		DIY floor insulation (susp. timber floors)
Systems &: Appliances	Heating	Room thermostat to control heating
		Thermostatic radiator valves
		Hot water cylinder 'stat
		Uninsulated cylinder to high performance
		Modestly insulated cyl to high performance
		Insulate primary pipework
	Lights and appliances	A++ rated cold appliances
		A+ rated wet appliances
		Efficient lighting
		Integrated digital TVs
		Reduced standby consumption
		Information and Communication Technology products
		Electronic products
Behavioural		Reduce household heating by 1 C
		Turn unnecessary lighting off
		Reduce heating for washing machines

3.2 Energy saving calculation

In the work performed by BRE for the CCC (see section 3.1) the annual energy saving figure for a particular measure, in a single household, was arrived at by modelling the energy consumption of an average UK household before and after the implementation of the measure. Due to changing building regulations and performance requirements for residential properties in the UK, a modelled typical UK dwelling will be different at any given year. Therefore a measure implemented in the typical home of 2012 will have a different energy saving effect to the same measure implemented in the typical home of 2017. The difference in the average UK home was accounted for and is demonstrated in Table 2 below.

The energy saving used in the analysis results from a measure being implemented in the 'Ultimate' dwelling, where "the values represent a house from a hypothetical future year, when all homes have been upgraded to a good standard for all the measures in the list" [25]. The energy saving for each measure modelled can therefore be considered conservative, as they are considered to be implemented in a home which is more energy efficient than the average UK household between 2012 and 2022. For example, a unit of solid wall insulation installed in the 'ultimate' home is modelled to save 8449 kWh per year, but it is modelled to save 8766 kWh per year in the average 2022 home.

Table 2.Impact of energy efficiency measures accounting for the time of implementation [25].

Energy Efficiency Measure	2012	2017	2022	Ultimate
Wall u-value	1.06	0.96	0.95	0.40
Roof u-value	0.37	0.24	0.22	0.16
Floor u-value	0.64	0.63	0.62	0.25
Window u-value	3.1	2.9	2.8	2.0
Door u-value	3	3	3	1.5
Infiltration rate	12.5	12.5	12.5	11.5
Boiler efficiency	79.5%	83.5%	86.2%	90%
HWC insulation mm	60	72	87	150
Primary pipework loss	49	46	43	40
Appliance factor	110%	111%	114%	115%
Cooking factor	100%	100%	100%	80%
No room stat	8%	7%	6%	0%
Thermo. Radiator Valves present	70%	80%	90%	100%
% low energy lights	30%	60%	90%	100%

The overall energy saving from a measure is broken up into different energy saving types; these are space heating, water heating and electricity. The magnitude of the saving for each of these categories is determined by the performance of each measure in the modelled typical UK dwelling. For example a solid wall insulation installation is modelled to save 8424 kWh/year in terms of space heating, and 25 kWh per year in electricity savings annually in the 'Ultimate' home. These combine to give an overall energy saving of 8449 kWh per year for the measure.

3.3 Translating energy savings to cost effective carbon reduction

The cost and carbon savings resulting from the energy saving – estimated as described in the previous section - depend on the relative amount of different energy sources that are in use; i.e. how much solid fuel, gas, oil or electricity, is used to heat the average household. Households across the UK use different sources of energy to heat space and water; some use gas, some use electricity, some use oil and some use solid fuels. This is represented in the modelling by the average home receiving a proportion of its space heating and a proportion of its water heating from each of these four energy sources.

Work has been carried out to extend the LCR model in order to adjust the proportion of each fuel used for space and water heating to the profile of each local authority as reflected through statistics. Figure 1 demonstrates the need to differentiate between the local authorities due to the extensive use of petroleum and solid based fuels in certain localities compared to the average as given in Table 3. These differences were also pointed out by stakeholders as reasons of reduced confidence in the results of studies based on a UK average residential fuel mix.

Table 3: Share of domestic energy use by end use and fuel for the average UK household [29].

	Fuel Mix	Gas	Oil	Solid fuel	Electricity
End Use	UK Average	65%	7%	4%	25%
Space heating	60%	80%	9%	6%	5%
Water heating	18%	84%	7%	1%	8%
Cooking / catering	3%	53%			47%
Lighting / appliances	19%				100%

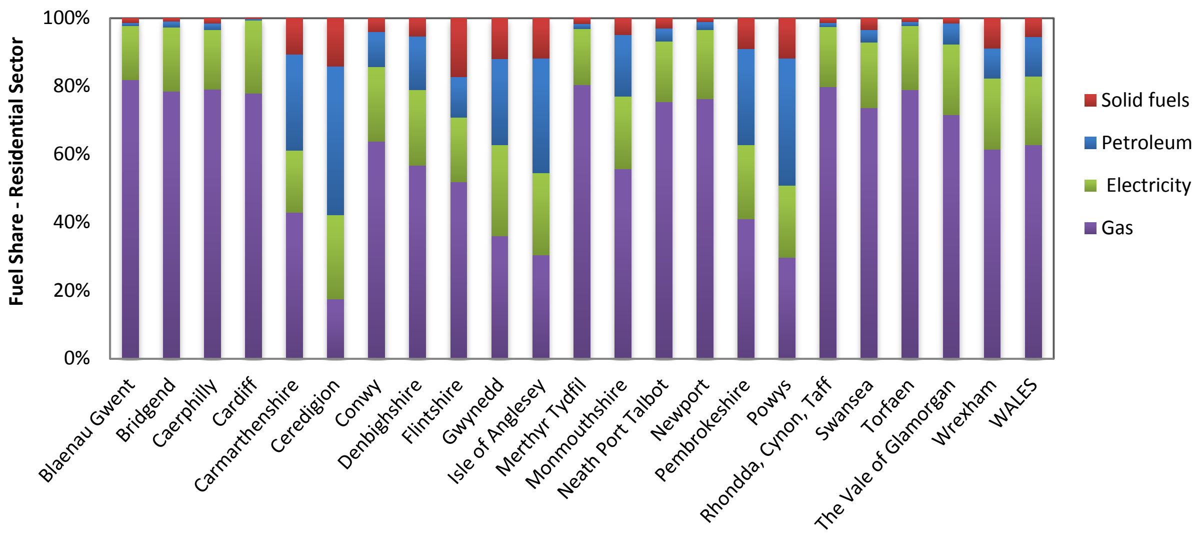

Figure 1: Share of different fuels in the residential energy consumption of Welsh local authorities and Wales. Data source: DECC [30]

As with the energy efficiency standards of homes the fuel mix for space and water heating will change over time, which is accounted for in the modelling. A short description of the methodology behind the estimation of specific fuel mix and emission factors [31] is given below.

3.3.1 Area-specific fuel mix estimates

The aims of this additional piece of modelling work is to translate the energy savings assigned to each measure to fuel and cost savings that reflect the fuel mix in each local authority.

This was achieved by correlating historical data on the contribution of each type of fuel to different domestic uses with the share of the respective fuel in overall domestic consumption [29, 32] and the information contained in the Home Energy Efficiency Database (HEED) [33]. The correlation revealed strong relationships between the two datasets and additional correlations between the use of specific types of fuel for space and water heating through time, which also related well with the HEED data expressing the geographical context. Examples are presented in Figure 2, Figure 3 and Figure 4.

These correlations were combined with the trends observed in the domestic energy demand projections [34] (Figure 5) to estimate the progression of the fuel mix within each of the local authorities. The same trajectory has been assumed, in terms of change in percentage per year, as giver in the UK level projections, to be taking place at local authority level as well, albeit from a different starting point.

While the methodology provides a way to attribute energy used for space and water heating to different fuels and come up with projections, it should be noted that fuel switch trajectories may differ depending on the starting point, the availability of technologies, resources and other parameters that cannot be accounted for in this study. Similarly in terms of the relationship between the fuel type used for space and water heating, the historical correlation may not be maintained going forward due to changes in technology. Renewables have been ignored as they only projected to account for 2.3% max of the mix by 2030 according to domestic energy fuel mix projections.

Having attributed the energy savings for each use to a particular mix of fuels the cost and emission savings are calculated from the fuel price projections [35] and the carbon intensity associated with each energy source through the use of established emission factors [36] (displayed in Table 4) These remain constant through the time frame of the study with the exception of electricity emission factors which are discussed in the following section.

Table 4: Emission factors used in the model [36]. The factor for electricity refers to the grid average at the start of the period modelled, and changes to fit the chosen scenario.

Fuels	**Emission factor $kgCO_2/kWh$**
Coal & Solids	0.31
Gas	0.18
Electricity	0.55
Oil	0.25

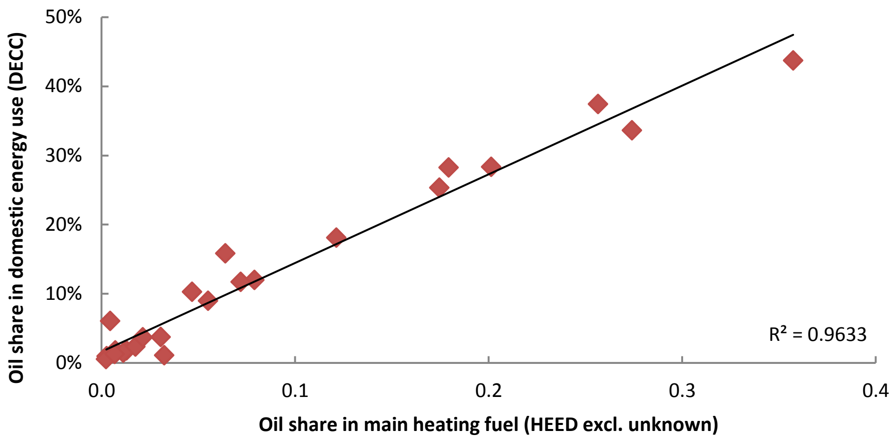

Figure 2: Correlation between oil share in HEED main heating fuel data and total domestic energy consumption. Each point represents a local authority. Data source: HEED [33], DECC [32]

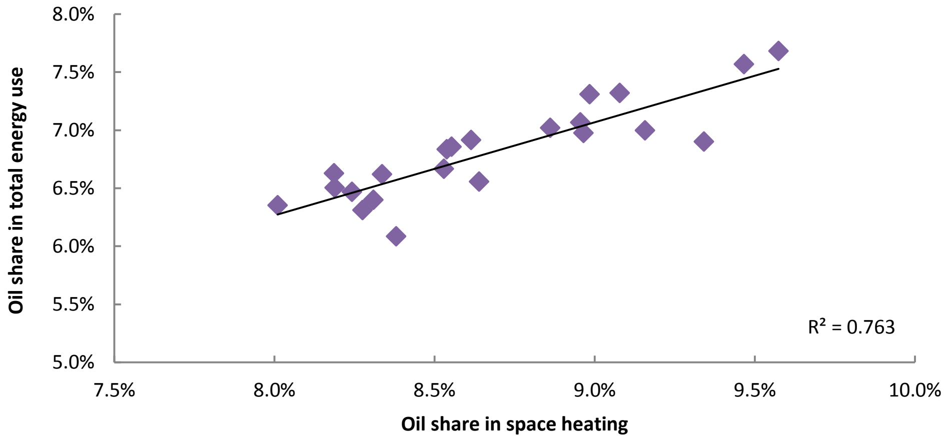

Figure 3: Historical correlation between the use of oil fuel in space heating against the share in total domestic energy at UK level. Each point represents a year. Data source: DECC [29]

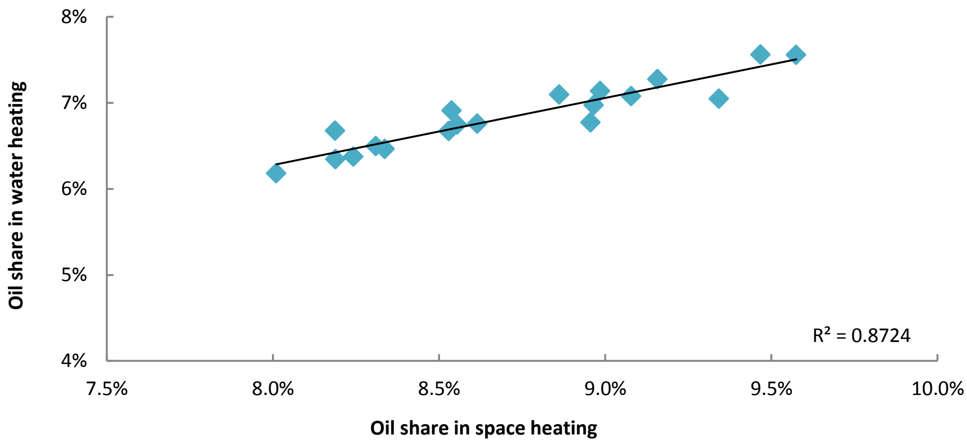

Figure 4: Historical correlation between oil (and other petroleum products) use for space and water heating at UK level. Each point represents a year. Data source: DECC [29]

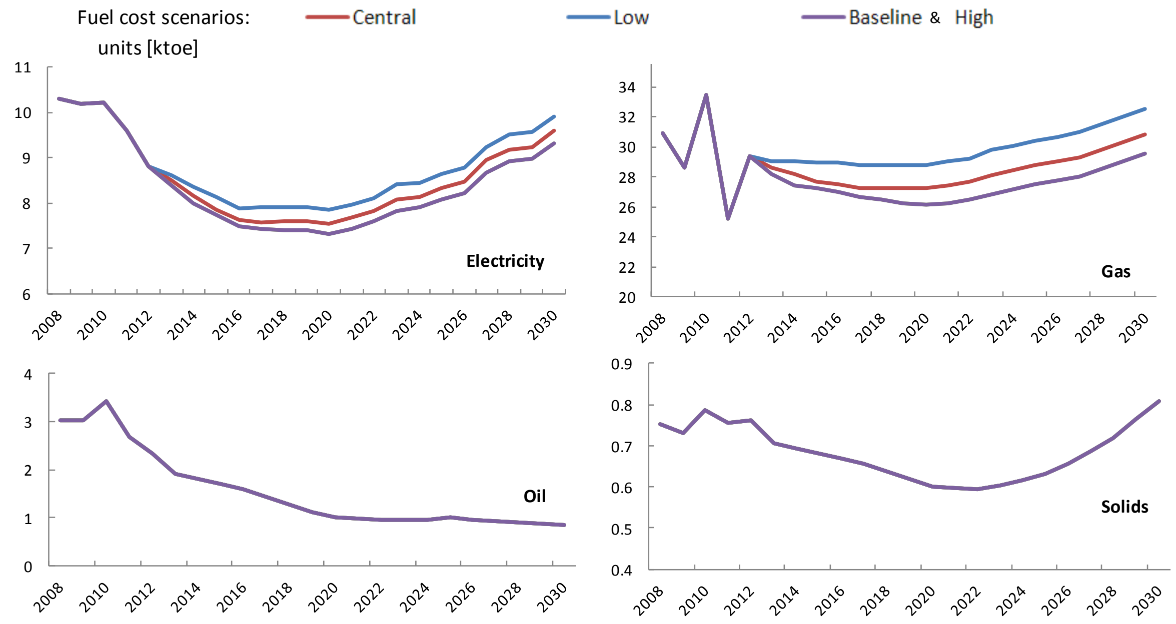

Figure 5: UK domestic energy consumption scenarios. Data source: DECC [34]

3.3.2 Choice of electricity emission factor

In the CCC work the marginal electricity generator was used as the relevant emitter in defining future savings, based on a Combined Cycle Gas Turbine (CCGT) plant with an emission factor of 0.38 kg CO_2 per kWh. However, it was noted that both a higher or lower factor could be assumed depending on the generation mix [26, 28].

Other literature also underlines the importance of the marginal emission factor of the large scale power generator at the time they come into effect [37, 38]. Work on the interaction of power generation emission and efficiency measures aimed at saving electricity found that using a grid average emission factor underestimates carbon savings [38] and advise the use of an incremental emission factor to evaluate the short term impact of such measures when the generation mix is presumed unchanged. These incremental factors were found to be up to 50% higher than the grid average; however, the research was inconclusive in terms of suggesting how to select suitable incremental factors as these were affected by type and magnitude of the savings as well as the specific fuel mix of the grid.

Further review of this work and others which seek to quantify marginal emission factors in connection with demand-side interventions [37] also concludes that these factors are usually higher than the system average as well as the long term marginal emission factor but has also uncovered instances where this might not be the case. Using marginal factors constructed in relation to specific measures were found to produce 30-60% higher impact than the average or long term marginal values. Nevertheless the uncertainty increases significantly when projecting the use of marginal emission factors into the future [37].

While, it is usual for work based on housing stock models to assume a single emission factor to account for emissions generated by the use of electricity in the domestic sector. Research which takes a more integrated, systems, approach has revealed this approach as being problematic [39], in that it does not take into account the actual generation mix and constraints of the power sector that may be evolving in parallel with the changes in the building stock. Long term modelling of the residential sector in parallel with decarbonisation scenarios, where the emission factor is endogenous based on the modelled grid, reveals much of the reduction in emissions to be due to changes in the power generation sector rather than efficiency measures [39].

This presents a challenge in terms of selecting emission factors for the current study. On the one hand previous research shows that the grid average underestimates savings but is inconclusive on how to define the marginal factor that should be used to calculate savings. On the other hand when modelling a number of interacting measures on a large scale that take place in the context of wider systemic changes, it seems counterintuitive to ignore the wider context of grid decarbonisation. Additionally, when looking at a large group of measures, in a medium to long term time horizon, when increased electrification is expected parallel to grid decarbonisation, relying on the marginal emission factor could result in a distorted picture of increasing emissions from the sector.

This study adopts a set of electricity emission factors that incorporate the decarbonisation trajectory of the grid in future years according to the fuel cost scenario chosen. The carbon intensity of electricity from the relevant fuels follows DECC forecasts [40] and reflects the projected fall in the carbon intensity of electricity in the period to 2022.

Nonetheless, the concept of incremental or marginal emission factors and the distinction of the savings in terms of grid decarbonisation versus the application of efficiency measures is certainly worth exploring further.

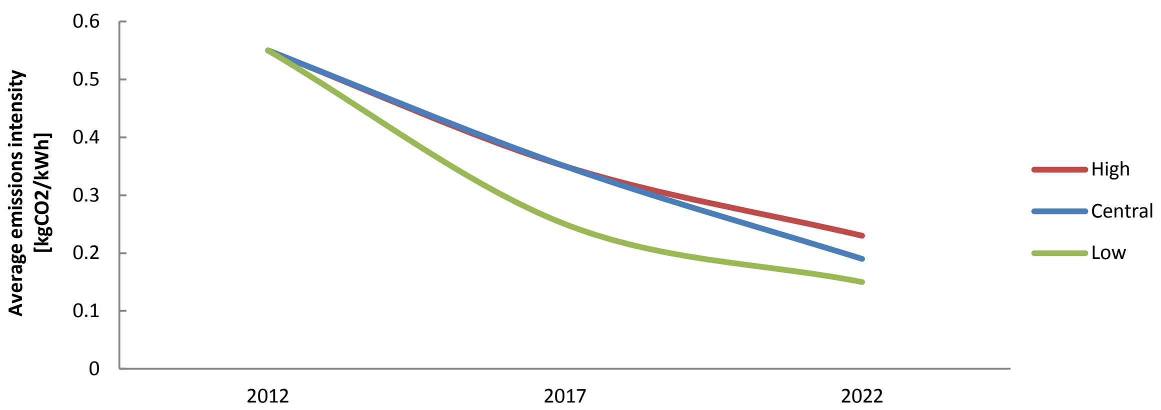

Figure 6: Average emission intensity forecasts for grid electricity, assuming the success of the electricity market reform for high, central, and low fossil fuel prices. Data source: DECC [40]

3.3.3 Cost effectiveness

The work that formed the background for the LCR model [28] had set out to investigate, on behalf of the CCC, what would be cost effective, in terms of abatement, in addition to what was going to be implemented in the context of a baseline scenario which included current policies and implementation rates. A variety of combinations of energy prices and discount rates, inclusive or exclusive of taxation can be explored through the model.

As mentioned in the above section on the carbon saving calculation, each modelled energy saving can be disaggregated into a corresponding amount and type of fuel avoided. The fuel types used in the model are oil, gas, electricity and solid fuels. The price paid by a residential property for each of the fuels is extremely variable and uncertain, even in the short term. The energy prices used in this modelling exercise are figures regularly published by DECC, and can be updated accordingly to reflect the most-up-to-date figures. The analysis and result presented in this working paper use the values published towards the end of 2012 [34]. These forecasts are available in 3 scenarios; low, central and high, and are available with and without tax. Private investment rates range between 8-25% while social rates are usually assumed at 3.5% [28]. The change in fuel type usage that was used to work out the carbon saving was also applied to work out the cost savings. As energy prices change, a measure implemented in 2022, for example, will have a different costs and savings profile than the same measure implemented in 2012.

4 APPLICATION DATA FOR THE WELSH LOCAL AUTHORITIES

The remaining potential at a national scale of the respective measures as contained in the CCC model does not consider economic or population growth. Information on the present amount of households and future projections for each of the local authorities in Wales [41] have been employed to transform the input on the basis of the data available on the household projections for the UK.

The calculation of how many instances of each measure would be implemented by a certain point in time in a particular region requires additional information to the CCC forecasts for the national measure uptake. In the CCC work national uptake rates are provided in the form of a technically possible amount or a 'Maximum Technical Potential' (MTP) and two scenarios which project what level of this potential may be feasibly implemented. The more conservative of the scenarios, the 'Extended Ambition' [27], was chosen for the LCR model and the levels of uptake where adjusted to account for scale i.e. the number of households that exist within a certain region compared to the nation, and for composition i.e. what level of measure implementation has already taken place in each relevant local area.

The Homes Energy Efficiency Database (HEED) [33] was used to obtain a location-specific picture of existing measure implementation, and concurrently the potential for each measure that remains. Data on the composition of energy efficiency measures per Local Authority have been extracted from the HEED and provided as input to the LCR model. Even though the HEED contains detailed information on measures relevant to the building fabric, it does not offer adequate levels of data for the compositional downscale of all the measures listed in Table 1. Measures for which regional data is not available are modelled according to the national uptake rates. This applies to the majority of behavioural measures and measures reflecting consumer preferences (e.g. appliances). The broad categories which have been included in the regional adjustment using information from the HEED are described in the following. The analysis also provides a snapshot of the different needs and progress rates across the local authorities in Wales.

4.1 The housing stock as represented in the HEED

The HEED records the uptake of sustainable energy measures and related survey data on a property basis combining data from an extensive variety of sources such as energy suppliers, government scheme managing agents, local authorities and other landlords, Energy Saving Trust (EST) Home Energy Checks as well as other EST programmes. Coverage in the HEED for the local authorities in Wales region is 57% on average, which under the guidance provided on the confidence levels for the data coverage, is reliable for analysis. Figure 7 shows the total number of entries in the HEED for each local authority in the region as well as the range and average of the sample size for each characteristic used in the model.

Records for each location indicate the number of homes that the HEED registers at least one piece of information for. The best coverage is observed for Gwynedd, where information exists for 99% of the stock; Ceredigion has the lowest amount of households registered at 45% of the total. The graph also shows the number of homes for which information about different property characteristics is available: main heating fuel has the best coverage; followed by data on the property age, external wall type; loft insulation; glazing type; and main heating system. These are used in the compositional downscaling of the potential savings for each local authority, assuming that the composition of the records in the HEED after exclusion of “unknown” entries is representative for the rest of the stock.

Figure 8 shows the levels of wall insulation (a), double glazing (b) and loft insulation (c) for the Welsh local authorities and the region in total; the UK is also shown for comparison. Entries in the HEED for loft insulation, wall insulation and double glazing cover, on average, 26-28% of the homes in Wales. The data shows that the majority of cavity walls appear to have been insulated, though some areas like Monmouthshire and Newport have more properties remaining to be treated than other local authorities. The share of solid wall buildings in the stock is markedly larger for areas such as Rhondda, Cynon, Taff, Ceredigion and Blaenau Gwent. The latter also shows an increased proportion of solid wall insulation, as does Torfaen. Merthyr Tydfil, Ceredigion and the Isle of Anglesey have the highest share of single glazed properties but there is potential to improve levels of double glazing across the region. Levels of loft insulation are quite good across the region, but areas such as the Vale of Glamorgan, Monmouthshire, Ceredigion and Bridgend are slightly worse off in terms of the thickness of loft insulation present in properties.

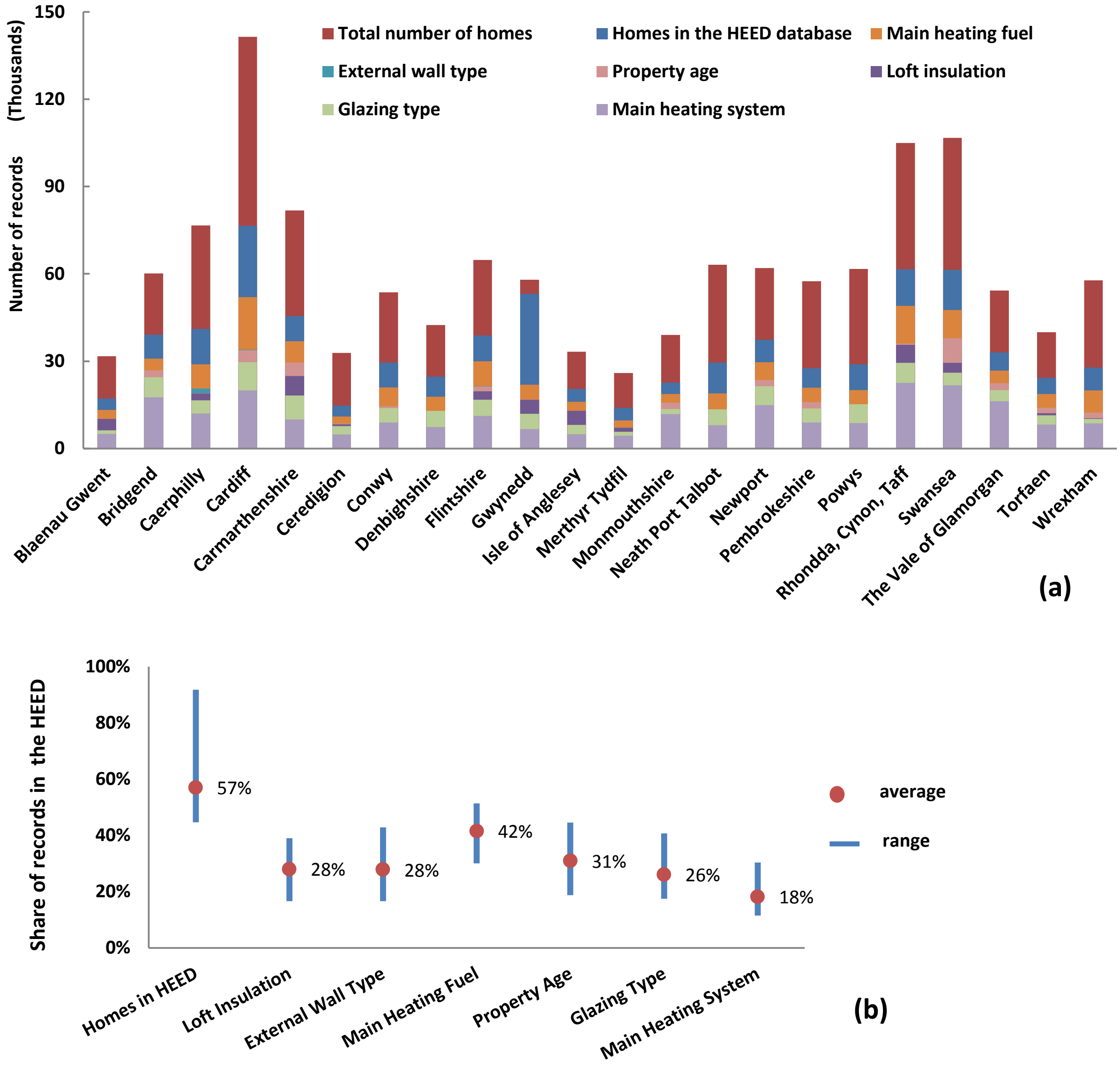

Figure 7. Number of known records for a number of building stock characteristics against the total number of homes ((a) overlapped graph) and range and average of the sample size for each characteristic (b) for the Welsh local authorities. Data source: HEED [33].

Along with the data on property characteristics, additional data on measures such as lighting and micro generation are available from the HEED at the regional level (Wales and England) which show the uptake of each measure. On the basis of existing uptake, the available potential can be derived for each energy efficiency measure. It should be noted that, except for compact fluorescent lighting, uptake levels recorded in the HEED are low and do not have a great influence on the remaining potential as outlined in the CCC scenarios.

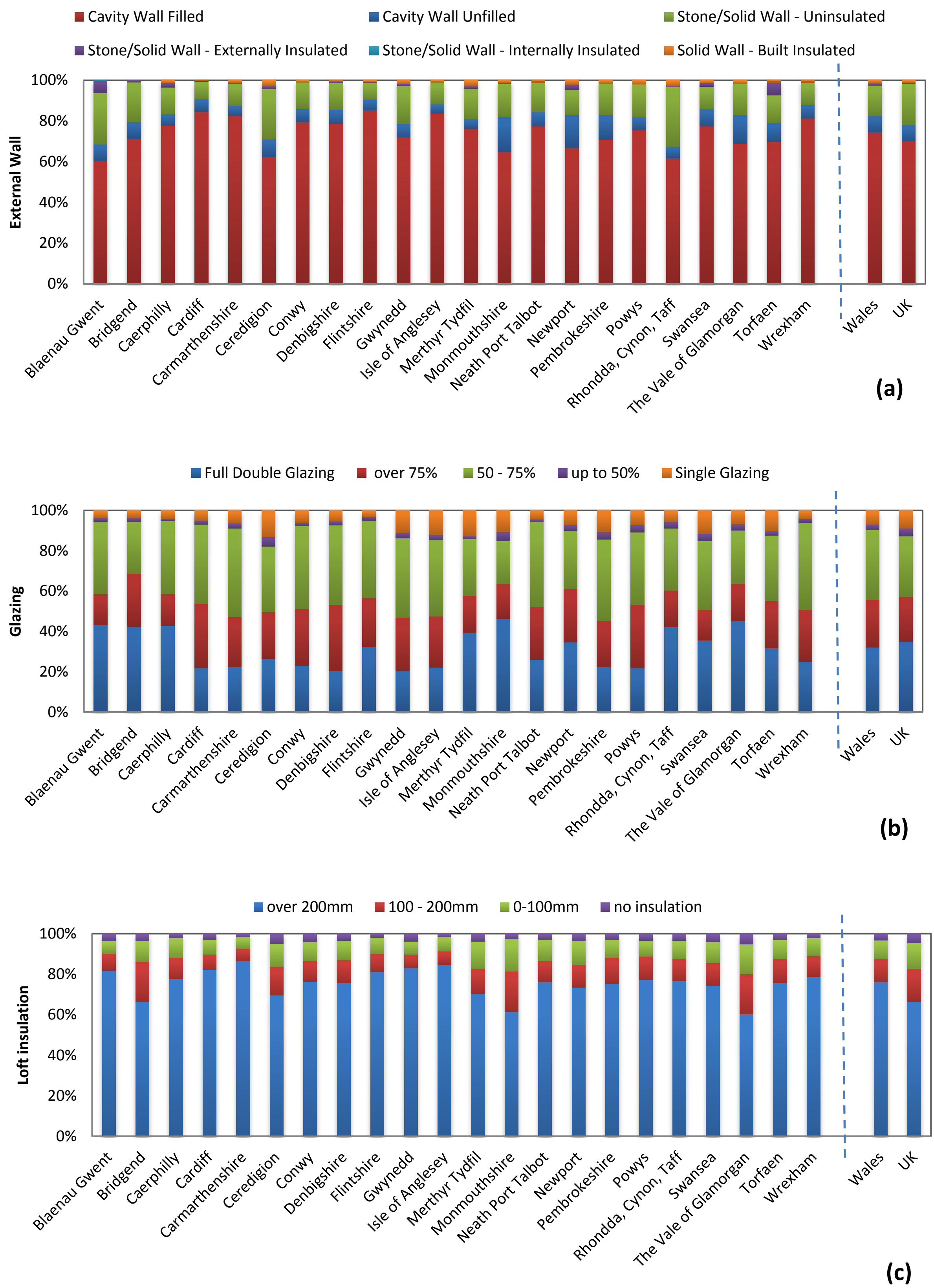

Figure 8: Wall insulation (a), double glazing (b) and loft insulation (c) figures for the Welsh local authorities. Data source: HEED [33]

5 RESULTS

For purpose of this study case we have selected to show results corresponding to high energy prices with taxation included, and a 7 % discount. The high fossil fuel cost scenario is chosen, in part, because it clearly displays the influence of regional characteristics, such as fuel mix, to the cost effectiveness, and thus deployment of measures. Selected results for the low fuel cost scenario are also given for comparison. The discount rate has been selected to be comparable to the rates available through the Green Deal. The results presented correspond to cost effective measures employed in the period to 2022. When comparing results per local authority, the relative size of the respective areas, as presented in Figure 7(a) should be noted, as much of the difference in saving potential arises from the respective number of households present. However, results for a number of measures do not follow that trend and are highly influenced by the stock as represented in the HEED, as well as the fuel mix of the areas considered. Normalised results are also provided, where possible, to further reveal the differences between the local authorities while accounting for the difference in size.

Most of the measures modelled in this study are “like for like” or increased efficiency substitutions for which the interactions have been modelled in the original work, so there is increased confidence in producing figures of total savings from the implementation of multiple measures. As described in the methodology section, double counting through overlaps has been avoided but it has not been possible to take all possible interactions into account, especially when it comes to additional measures. These measures, such as behavioural changes and electronics and ICT, can still be ordered in terms of cost effectiveness. Even though, investigations for the domestic sector suggest that not accounting for interactions between measures does not alter the results significantly given all other uncertainties [28] caution is advised when producing cumulative results which contain any of the additional measures.

Behavioural measures and measures regarding electronics and appliances are downscaled but not adjusted to the particulars of the local authorities due to lack of specific data. The average trend assumed for the UK is therefore maintained throughout, but the local fuel mix is taken into account in terms of the savings achieved. Building fabric measures are adjusted based on the building stock of each local authority. This accounts for the variation in the results, which is analysed separately.

5.1 Cost effectiveness

Much of the work of the CCC as well as the LCR model concentrates on producing Marginal Abatement Cost Curves (MACCs) for CO_2 emission reductions from the adoption of the specific measures in the residential sector. These can also be produced for the local authorities in Wales; an example is shown in Figure 9 for Blaenau Gwent.

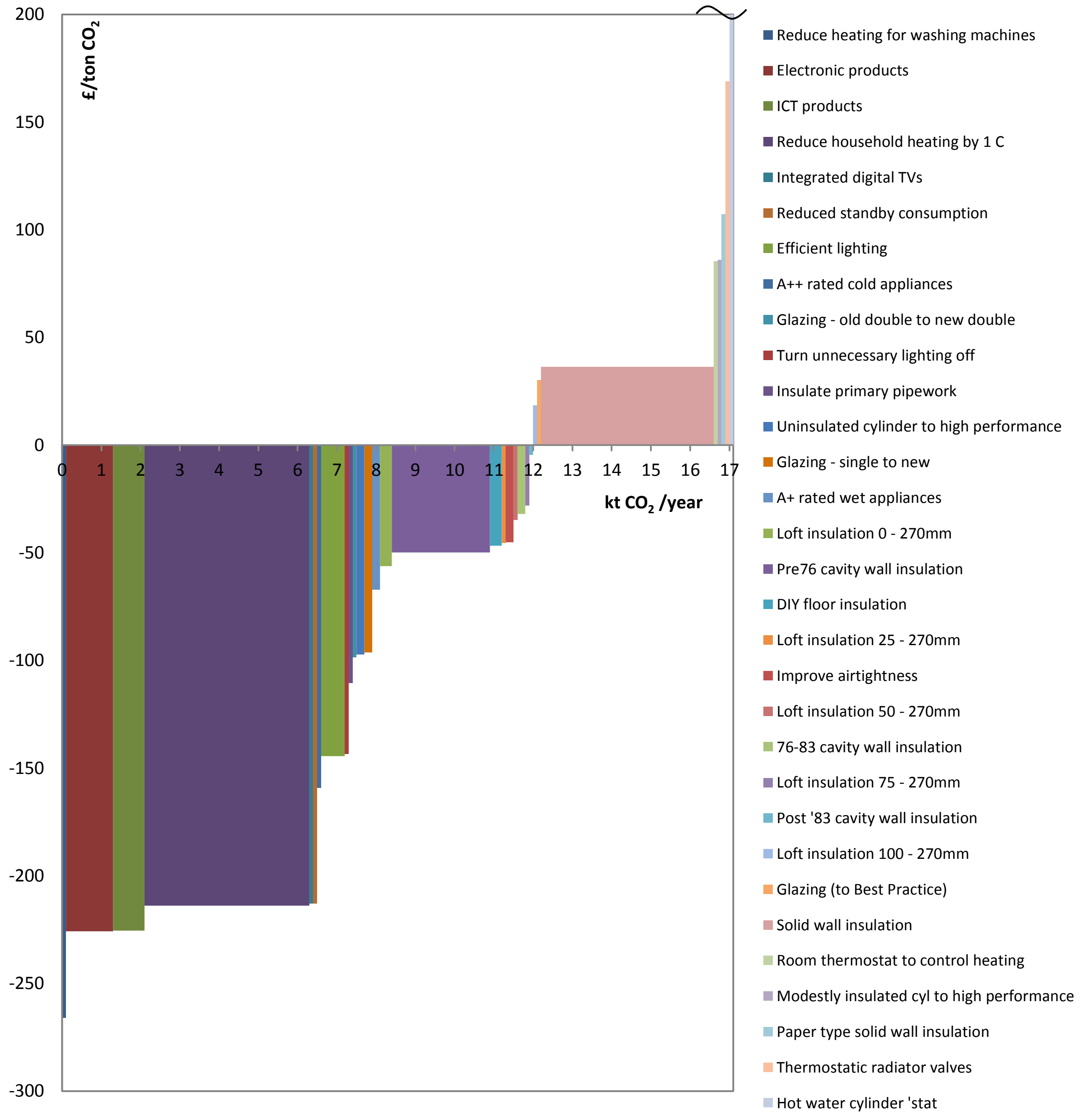

Figure 9: MACC for the Blaenau Gwent local authority for the high fuel cost scenario and a 7% interest rate with taxation included. Measures displaying negative values are cost-effective, i.e. saving money over the period studied.

The MACCs provide information on the order of measures in terms of cost effectiveness (negative values denote savings) but due to the additional measures being included, and the uncertainty over interactions, estimates on the amount of cumulative savings are more uncertain. The four measures emerging as most cost effective for the period to 2022 are in fact additional measures (behavioural, electronics, ICT), followed by measures concerning lights and appliances. Most of the cost effective building fabric measures offer more modest monetary savings. Cavity wall insulation for properties constructed before 1976 stands out as a measure with significant emission saving potential. On the other hand, high levels of loft insulation, glazing to best practice and solid wall insulation prove too expensive for the particular area compared to the potential monetary savings.

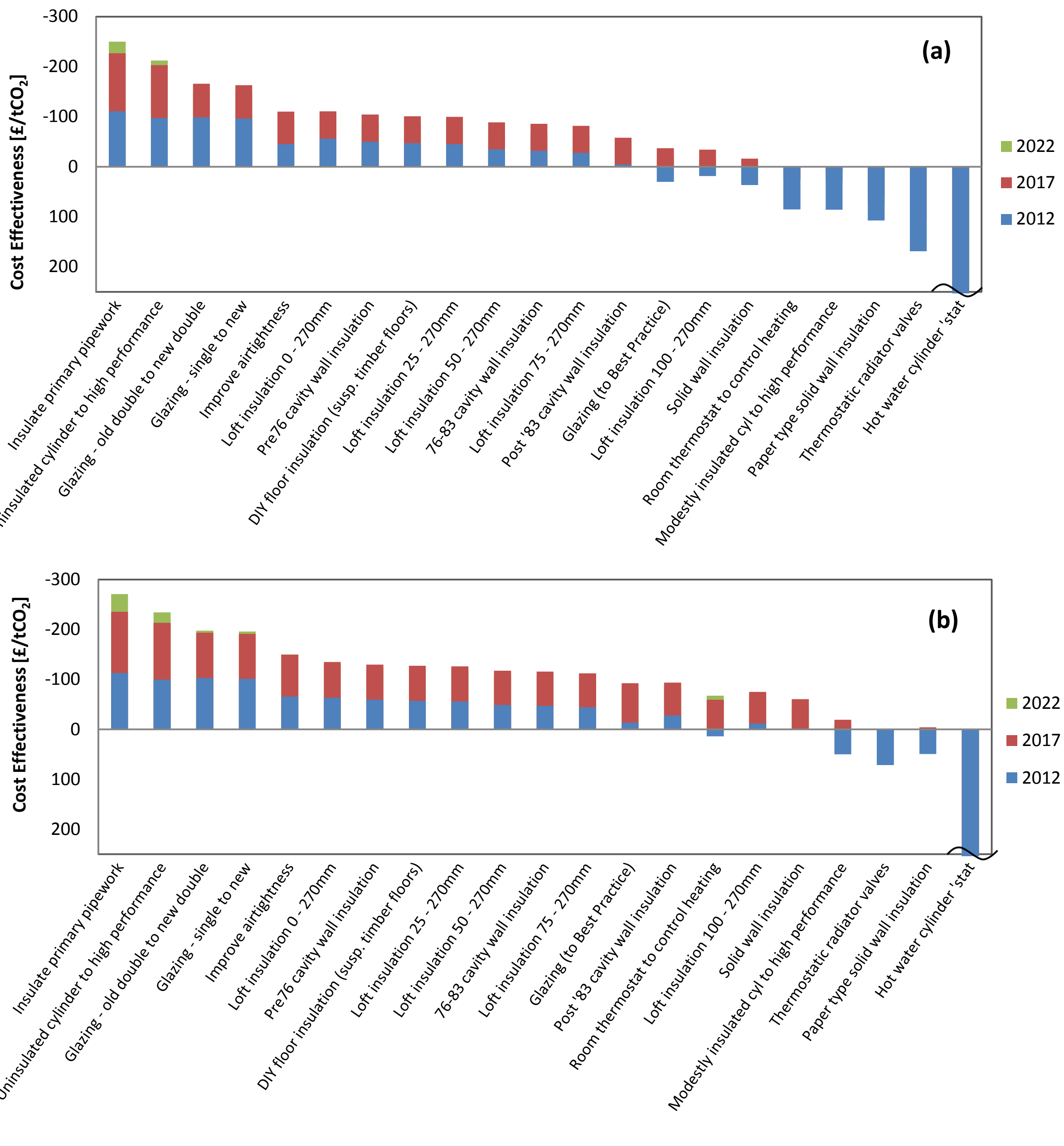

Figure 10: Cost effectiveness of selected measures for Blaenau Gwent (a) and Ceredigion (b) for the high fuel cost scenario and a 7% interest rate with taxation included (overlapped graphs). Measures displaying negative values are cost-effective, i.e. saving money based on the costs at the time.

Figure 10 shows an alternative way of displaying cost effectiveness of each measure as it appears at each time step of the calculation (note that the chart is overlapped and only includes building fabric and certain systems measures). This provides an indication of the incentive or trigger that would allow measures to be implemented in each period, dependent on the scenario and particulars of each local authority. Note that any differences between Figure 9 and Figure 10 stem from the fact that the first is based on values at the end of the period, taking into account that cost effectiveness for most measures reduces towards 2022. In contrast, if a snapshot is taken of the evaluation for the measure for 2017 this may appear cost effective given the costs for that period. We do not assume perfect foresight, so if a measure is viable in a certain period, then implementation takes place until the potential is reached or the trend is reversed in a subsequent time step.

Figure 10(a) shows results for Blaenau Gwent for the high fuel cost scenario and a 7% interest rate with taxation included, while Figure 10(b) shows results for Ceredigion for the same scenario. These two local authorities are chosen for comparison as the best example of how the residential stock and fuel mix within a local authority can influence the cost effectiveness of measures as these two are among the most diverse. Comparing the two local authorities it is evident that the measures which are cost effective, the priority order, as well as the magnitude of the savings differ significantly. Ceredigion has the lowest share of gas in the residential fuel mix, which means that, on average, cost for space and water heating is more expensive and there is more incentive to achieve savings asmeasures will pay off in a shorter period of time. Figure 11 shows the opposite effect for Blaenau Gwent when changing assumptions for future fuel costs from the high to the low fuel price scenario. Compared to Figure 10(a) monetary gains from the implementation of all measures are reduced and number of (the more costly) interventions are not cost effective under these assumptions.

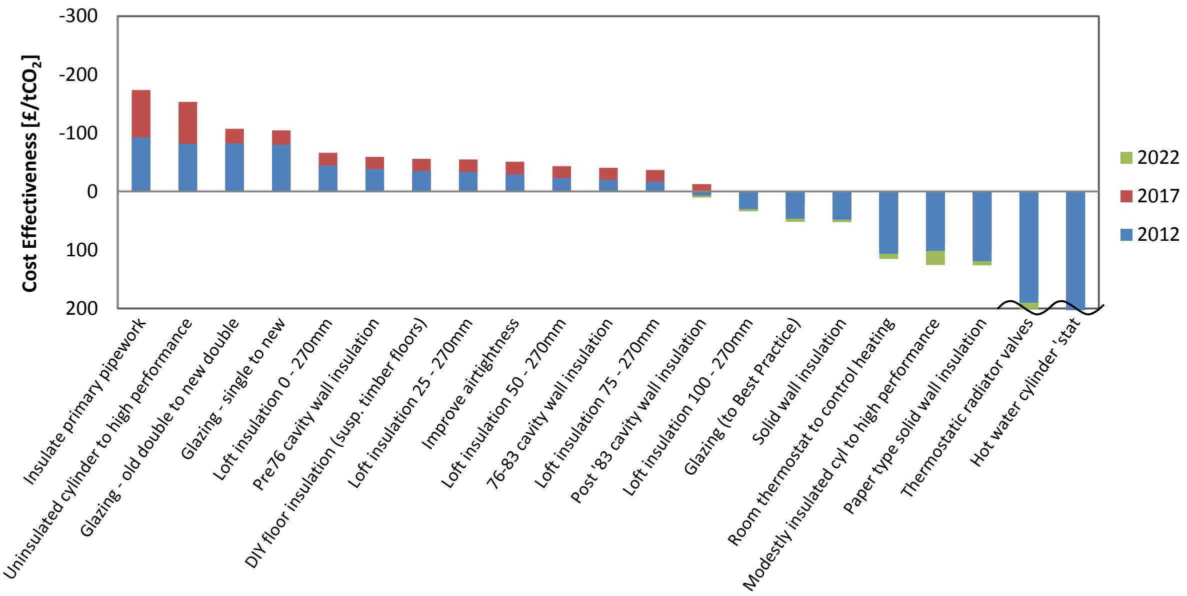

Figure 11: Cost effectiveness of selected measures for Blaenau Gwent for the low fuel cost scenario and a 7% interest rate with taxation included (overlapped graph).

5.2 Measures not affecting the building fabric

Figure 12 shows the potential savings from measures relevant to lighting, household appliances, electronic devices and behavioural change. As mentioned in previous sections, a number of these measures are additional to the original work and the effect of interactions with alternative efficiency applications is not taken into account. For this reason they are shown separately, as single measures across the city region.

Electronic products show the most potential for savings out of electronics and appliances, followed by Information and Communication Technology (ICT) products and efficient lighting. Regarding investment, efficient lighting and A+ rated wet appliances are the most costly interventions, requiring 58% and 41% of the budget in this group of measures by 2022. However, this is an area where regulation for new products as well as incentivising the potential rate of replacement of existing technology in operation could be more difficult to achieve.

In terms of behavioural measures the changes included are reducing household and washing machine heating and turning off unnecessary lights. The major impact in this category comes from reducing household heating by 1C. Behavioural measures have some costs associated with their research and implementation but these are minimal compared to the investment required for other interventions. There is very little adjustment in the potential of behavioural measures between different fuel cost scenarios in the present modelling process.

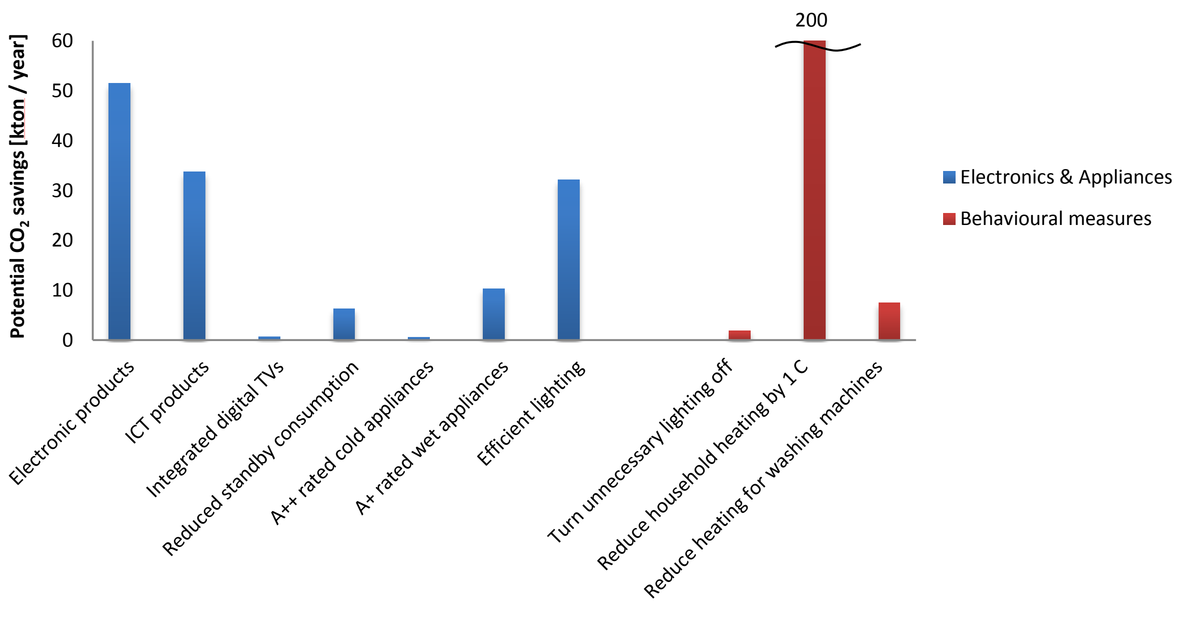

Figure 12 Potential annual CO_2 savings by changes in household appliances and electronic devices and behavioural changes for the local authorities in Wales.

5.3 Building fabric measures

Figure 13 and Figure 14 show the potential for CO_2 savings by building fabric measures and the respective investment needed. The interventions are grouped by type into: increasing wall or loft insulation; better glazing; or a number of other measures. Wall insulation has by far the most potential for emission reductions but also the highest associated cost accounting for just over 64% of the potential savings and 79% of the investment needed. Various levels of loft insulation and changes in glazing follow in terms of the carbon reduction potential, while a number of other measures such as DIY floor insulation and improvements in air tightness also make a small cost effective contribution.

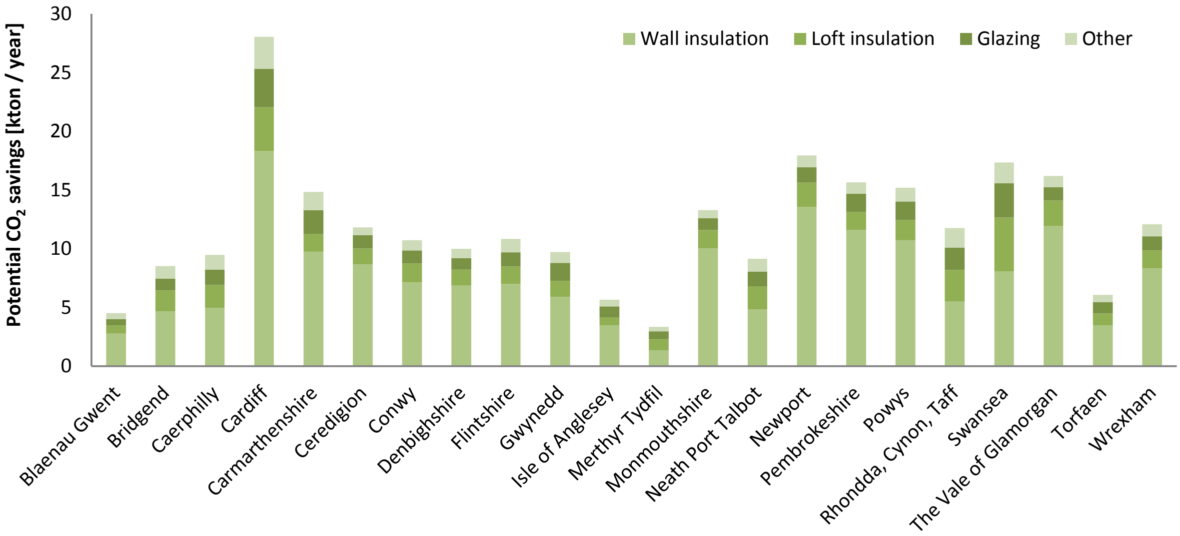

Figure 13: CO_2 emission savings broken down by type of building fabric measure for each local authority.

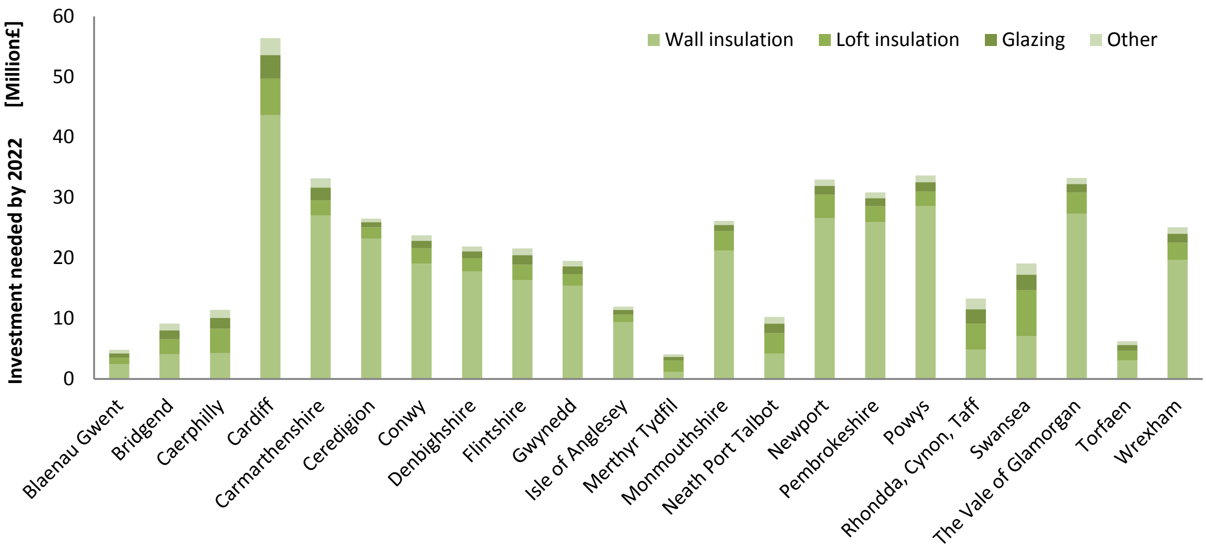

Figure 14: Investment needed by 2022 in each area of building fabric measures per local authority

Note that the trend in both the emission reduction potential and the necessary investment does not always correlate with the relative size of the local authority as provided in Figure 7(a). This is due to the differences in the residential stock in each location as recorded in the HEED, and the difference in fuel mix, which is reflected in the calculations.

Figure 15(a) gives an indication of the number of cost-effective building fabric interventions necessary to achieve the emission reduction levels shown in Figure 13, while Figure 15 (b) shows the reduction in measures that can be retrofitted cost-effectively under a low fuel cost scenario. In the high fuel cost scenario almost 280 thousand properties in the Welsh local authorities could benefit from cost-effective improvements in loft insulation by 2017. This is reduced to fewer than 144 thousand interventions if low fuel costs are assumed. Solid wall insulation does not feature in a low fuel cost scenario, while loft insulation and glazing measures are also substantially reduced, as it is no more cost effective to pursue them to best practice levels. Conversely, cavity wall insulation and the remaining building fabric measures examined are not affected by the magnitude of change in fuel cost between the two scenarios.

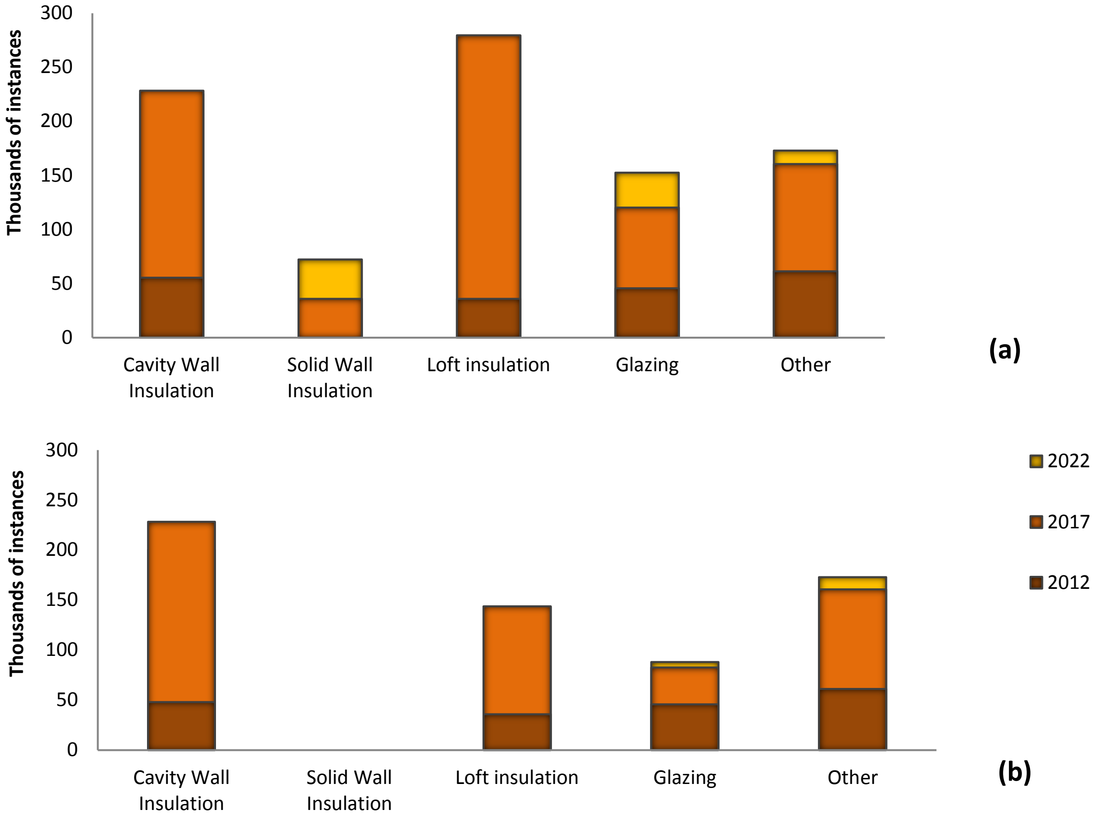

Figure 15: Scale of cost effective building fabric interventions for the Welsh domestic sector in the high (a) and low (b) fuel cost scenarios.

Finally, Figure 16 combines all the above information presenting emission savings relative to the share of investment and retrofit instances in each category of measures. Loft and wall insulation count the most instances, or retrofitted households, but when it comes to investment and CO_2 savings, it is wall insulation that requires most of the funding but also delivers the highest emission cuts. A more detailed look within the wall insulation options reveals that cavity wall insulation in pre '76 construction properties can deliver large CO_2 savings (57% of the potential) at reasonable cost (16% of the total estimated investment). Similar comparative graphs can be produced in more detail for each category, or including just a selection of measures to aid (along with other factors) decisions on the allocation of funds and priority of measures in each area.

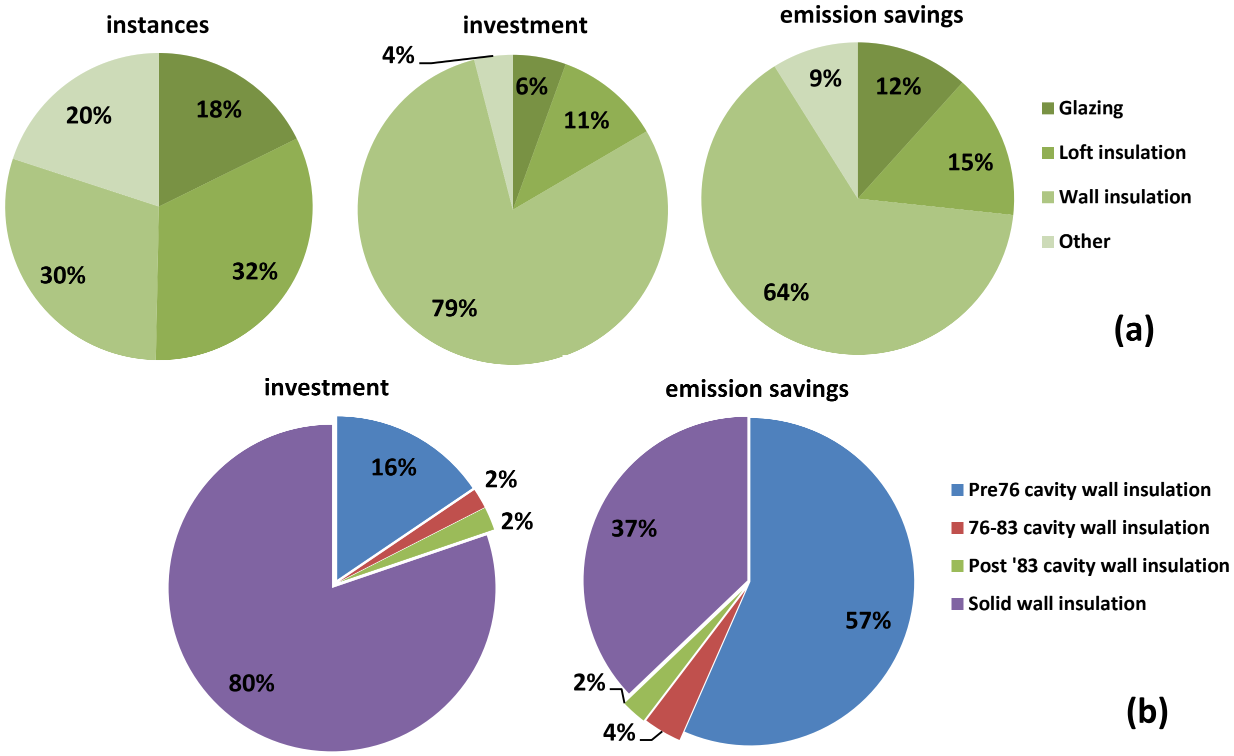

Figure 16: Split of cost effective instances, investment and carbon saving potential between different types of building fabric measures for Wales (a) with further breakdown of the investment and emission savings for wall insulation measures (b).

Figure 17 and Figure 18 provide a more detailed picture of the cost effective measures in each category in terms of CO_2 savings and investment requirement respectively. These are discussed further in the following sections where each of the building fabric measures is analysed in relation to the input data. Finally, Figure 19 provides the potential for CO_2 savings, as estimated by the model, normalised by the number of households in each local authority. This is done to remove the effect of the size of the local authority so that all differences can be attributed to the condition of the stock, the specific fuel mix, or a combination of the two. Ceredigion, Monmouthshire and the Vale of Glamorgan emerge as the areas with the greater potential for emission reductions relative to their size.

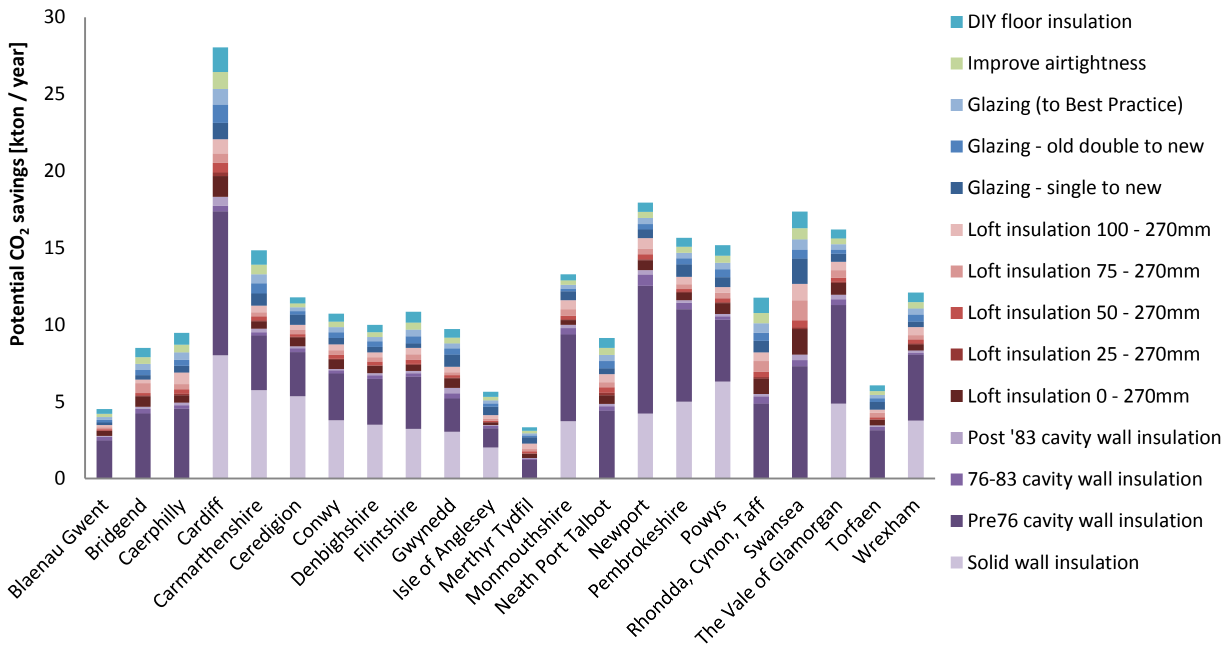

Figure 17: Detailed potential annual CO_2 savings from cost effective building fabric measures per local authority.

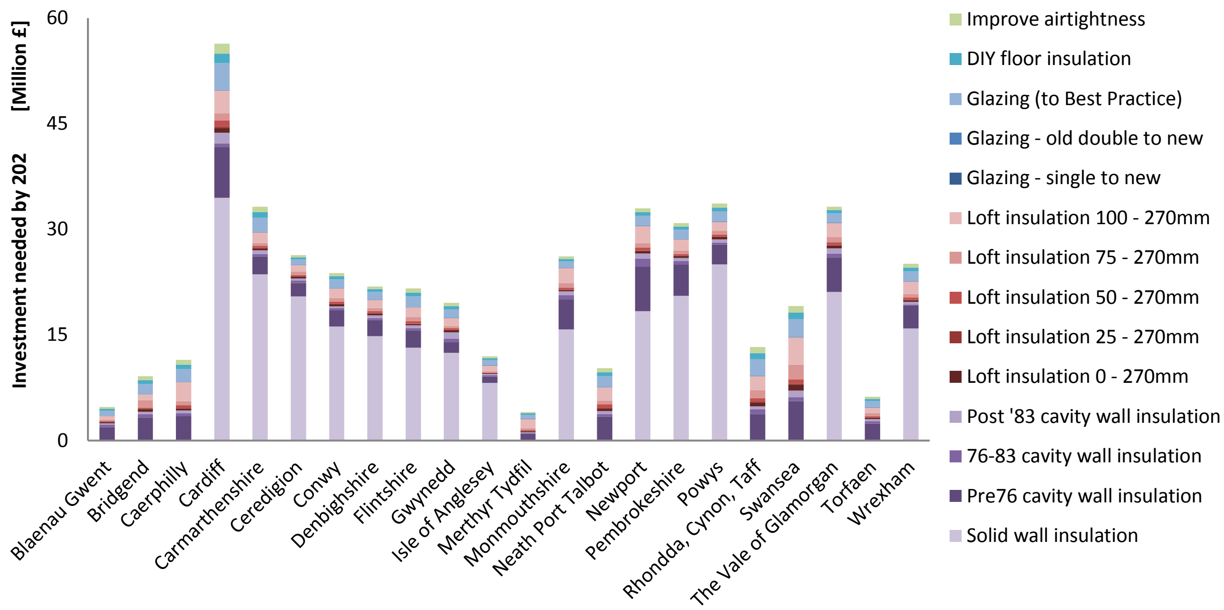

Figure 18. Detailed investment required in cost effective building fabric measures by 2020 per local authority.

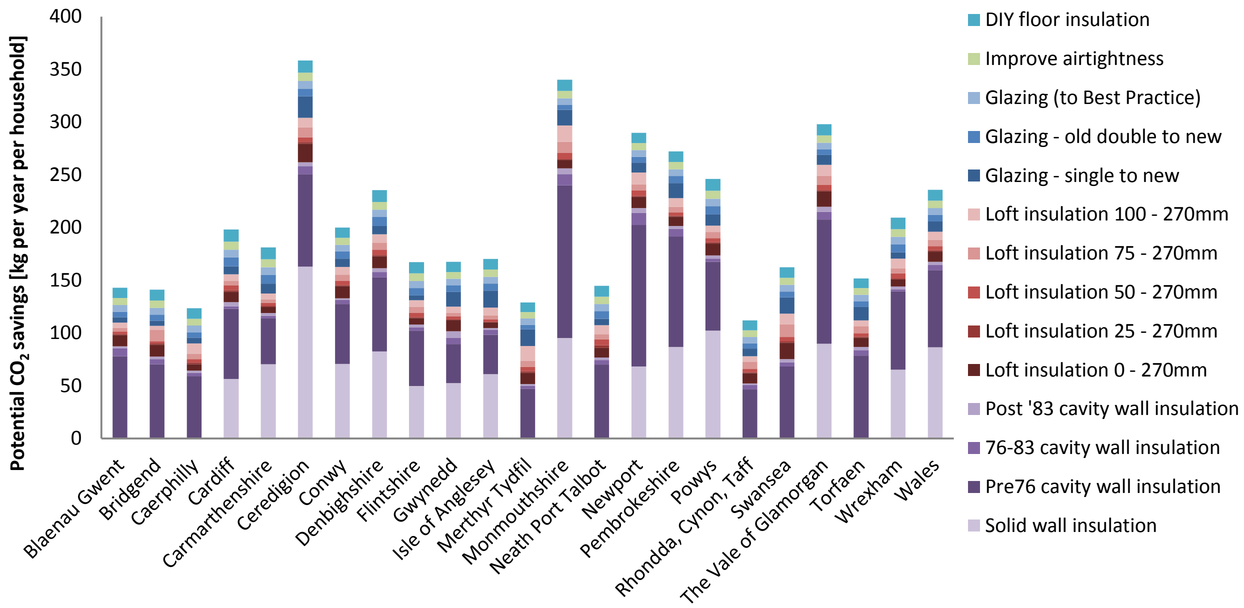

Figure 19: Detailed potential annual CO_2 savings from cost effective building fabric measures per local authority normalised by the number of households to account for the difference in size.

5.3.1 Wall insulation

Wall insulation measures are divided into solid and cavity wall based on the type of wall; cavity wall insulation is split further based on the age of the property to pre'76, '76-'83, and post '83 construction. The first thing to note is that solid wall insulation is not cost effective across the region, but in 15 of the 22 local authorities (see Figure 17). These are not necessarily local authorities with larger proportion of solid wall dwellings in the housing stock, but rather areas where the fuel mix for space heating is such that it makes solid wall insulation cost effective for the given fuel cost scenario. As shown in Figure 20, in the period 2012 – 2017, when solid wall insulation measures start to feature in the results, these local authorities have the highest fuel costs for space heating; there seems to be a marginal cost around 6.3 pence/kWh where the measure becomes cost effective. The same figure also shows the relationship between the share of different fuels and the cost of space heating (on average) for the local authorities in the region. Comparing the three columns displayed it is evident that it is the share of electric heating rather than oil and solids that drive cost in this particular scenario; contrast, for example, Cardiff versus Monmouthshire. Increasing electrification in order to combat emissions through grid decarbonisation could drive costs up, unless effective energy efficiency measures and market reforms take place. Figure 21 shows that these particular local authorities also have higher emission factors for space heating relative to the rest of the region. If low fossil fuel costs are assumed solid wall insulation is not cost effective across the board.

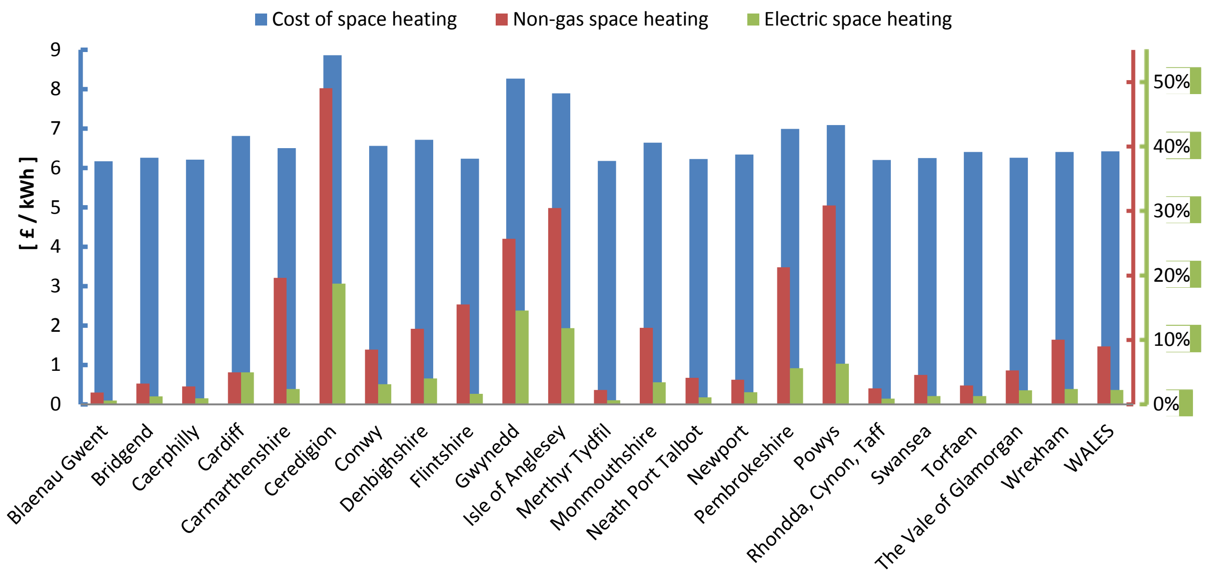

Figure 20: Estimated cost for space heating in 2017 in the high fuel cost scenario (blue series and axis), and correlation with the share of non-gas (red series and axis) and electric (green series and axis) space heating for each local authority.

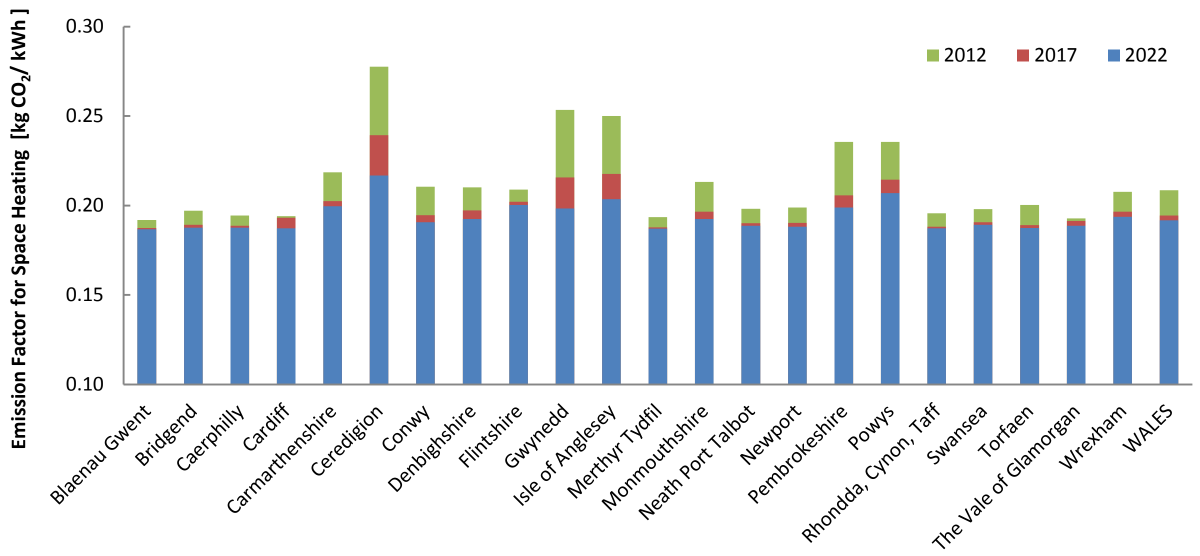

Figure 21: Projected emission factors for space heating in the Welsh local authorities for the high fossil fuel cost scenario.

Pre'76 cavity wall insulation accounts for 56% of the potential for CO_2 savings from wall insulation in the region, at 16% of the cost effective investment modelled. Solid wall insulation contributes a further 37% of CO_2 savings but requires 80% of the funding for the implementation of wall insulation measures to 2022, even though it is only deployed just over half of the local authorities, as solid walls are much more expensive to treat.

According to these figures, the greatest initial gain could be obtained by targeting older (pre ’76) properties with cavity walls. Figure 14 shows that there is scope for saving through this intervention across Wales. Figure 19 shows that Monmouthshire, Newport and the Vale of Glamorgan all have high potential for this measure relative to their size; the HEED data indicates that 18-20% of the stock in these local authorities falls within this category.

5.3.2 Loft insulation

The potential for CO_2 emission reductions by installing loft insulation is split between introducing insulation to uninsulated or poorly insulated properties and upgrading the insulation of moderately insulated properties to a high standard. Uninsulated properties account for 34% of the potential for reductions from this measure at about 10% of the total necessary investment. At the other end of the scale, upgrading insulation from 100mm to 270mm would cut annual CO_2 emissions a further 26% of the potential, requiring 55% of the estimated investment.

Up to 5% of the surveyed stock in The Vale of Glamorgan has no loft insulation, and in total up to 28% of the stock in local authorities such as Monmouthshire and The Vale of Glamorgan is considered for the loft insulation measures presented here. Taking into account both stock condition and size Swansea is the local authority that could achieve the greatest savings from this measure.

5.3.3 Glazing

Double glazing is a popular measure the implementation of which often happens for reasons unrelated to energy efficiency [25]. The change from single to (E rated) double glazing is mandatory for extension and/or renovation work and for that reason it is considered unaffected by the modelled policies and no costs are assigned to the measure. It is estimated that the stock will be fully replaced by 2035 [27].

In the case of glazing measures, potential savings are shared between replacing single and old double glazing in most cases, except for local authorities where the share of single glazing is high, such as Merthyr Tydfil, and Swansea (12-13% of the stock). Replacing single glazing to double would bring about 42% of the potential savings, a further 28% of the potential reduction in CO_2 emissions could be achieved by replacing old double glazing. The remaining 30% in CO_2 savings is the most expensive to achieve, requiring glazing to best practice. Note that glazing to best practice has not been adjusted through the use of HEED data and consequently the potential for this measure is only dependent on the size of the local authority. Glazing to best practice is not cost effective if low fossil fuel costs are assumed.

5.4 Prioritising measures

The tables included in the Annex provide a comparative view of the measures for each local authority, as well as the effectiveness of each measure across local authorities. All values given in the tables are for cost effective measures; blank cells indicate that the measure is not cost effective in this local authority for the assumptions made in the current scenario. The assessment is made on the basis of the description of the housing stock and fuel mix through large scale statistics; it does not imply that the measures will not be cost effective for particular households and vice versa.

Table A.1 shows the estimated potential for annual CO_2 savings by 2022 as a result of the cost effective measures modelled in the study. A total of 273 kton of CO_2 could be avoided annually across Wales by the measures included in the table. The measures contributing the most, in absolute terms, to overall savings are pre ’76 solid wall insulation and solid wall insulation. Cardiff is the area with the greatest potential – which is to be expected given the difference in size from the other local authorities.

Table A.2 shows the potential displayed in Table A.1, normalised by the size of each local authority in terms of number of households. This is done to eliminate the influence of the size of the local authorities and reveal more about the influence of the housing stock and fuel mix in each location. The table has been colour coded by column in order to reveal the local authority in which the greatest potential for savings lies by measure. For example Ceredigion has the potential to achieve high savings form replacing single glazing – on average 20.4 kg CO_2 per household annually, compared to the lowest potential for this measure which is 4.6 kg CO_2 per household annually for Flintshire. Similarly, in Monmouthshire, pre ’76 cavity wall insulation has the potential to achieve annual savings of the order of 144.8 kg CO_2 per household compared to 37 kg CO_2 per household per year for Gwynedd. The different potential between local authorities as displayed here is a function of two things – the prevalence of properties receptive to a particular measure in the stock and the type of fuel (i.e. the number of properties off grid) in a particular area. The last row indicates the average saving from each measure across Wales, while the last column shows cumulative savings per household in each local authority from cost effective measures.

Table A.3 isolates the effect of the fuel mix further by normalising the potential for CO_2 savings by the number of instances in each local authority. An average for each measure across Wales is also provided. While Table A.2 also includes the influence of the density of stock appropriate for retrofit, Table A.3 refers to an actual instance; a household retrofitted in a particular location displays different savings because of the average fuel mix in the particular local authority. Table A.3 is colour coded by row, highlighting the most effective measure in terms of carbon savings for the average household in each local authority.

Table A.4 and Table A.5 show the distribution of potential savings across the different types of measures and local authorities respectively. Table A.4 (colour coded per row) highlights which measures have the greatest cumulative potential per local authority. Solid wall insulation – where cost effective – and pre ’76 cavity wall insulation are the measures that stand out irrespective of location. In Table A.5 (colour coded per column) the effect of the relative size of the local authority has a big influence and as a result Cardiff shows the greater potential for overall reduction for most of the measures considered.

The influence of the share of particular property types in the stock is discussed further in Table A.6 and Table A.7. Table A.6 (colour coded by column) shows absolute figures for the number of households that would be cost-effectively retrofitted with each measure under the scenario modelled. The effect of size is again prevalent with high numbers of properties located in the largest local authorities. This influence is removed in Table A.7 where the retrofit instances are displayed as a proportion of the number of households. The table is colour coded by row to highlight which measure has the most potential in the stock. However, if figures are compared across each column there is a notable difference in the percentage of properties that could receive the measures across the local authorities. For example in Monmouthshire and Newport between a fifth and a quarter of all households are featuring as candidates for pre'76 cavity wall insulation. Cardiff, which displays the highest absolute figures in Table A.6 is ten percentage points below these local authorities in terms of share in the stock. While further research is necessary on the distribution of the stock, it may be easier to create retrofit clusters in areas with higher density per measure.

Table A.8 shows the estimated costs for the implementation of all cost-effective retrofit measures modelled under the high fuel cost scenario (EMR grid decarbonisation, 7% interest rate, taxation included) to 2022. The investment could amount to just under half a billion across Wales.

The figures from Table A.8 are normalised by the size of the local authority in Table A.9. The table is colour coded by column, showing the local authority where most investment is necessary per measure relative to size. The last column shows the average investment estimated per property for each local authority, while the last row provides the average per measure across Wales.

Finally, Table A.10 and A.11 show the cost-effectiveness of the each measure for the local authorities based on the Net Present Value of cost and carbon savings as calculated in the three modelling time steps. These are very indicative as they rely on the assumption that these cost and carbon savings will be maintained for the lifetime of the measure. It is also useful to note that glazing measures (except glazing to best practice) have not been assigned any costs as they are included in current building regulations. Nonetheless, the tables provide a measure of the change in cost-effectiveness under different cost assumptions; as in previous graphs, negative values indicate monetary savings.

5.5 The impact of electricity share and emission factors

It is worth revisiting the effect of the choice of electricity emission factors on the resulting carbon savings. For example the local authority of Cardiff has an overall 11% share of electricity in the fuel mix for the year 2022, 6% of which is used for space and water heating. If the high fuel cost scenario is assumed the carbon savings based on the grid average (as modelled) and the marginal emission factor assumed by the CCC would be 68 and 89 kt per year respectively by the year 2022. The difference between the two estimates is considerable but only indicative; results will be different for each local authority. Since the difference between the marginal and grid average factor becomes significant past the year 2017 when the majority of the cost effective measures should already have been implemented there is very little impact in the number of instances and investment modelled. The main impact is in the carbon saving estimates where the grid average approach could be considered as providing a more conservative end result.

5.6 Cumulative investment and potential CO_2 savings

Figure 22 shows the cumulative upfront investment required in order to implement all cost effective measures presented for the Welsh local authorities. In the high fuel cost scenario, around 84 % of the total investment estimated to 2022 is required to retrofit the building fabric, with the rest covering the cost of changes in systems and appliances and a relatively small contribution from costs relating to introducing behavioural measures. In the low fuel cost scenario the potential investment in cost effective measures is down to a third of the high fuel cost scenario estimate, as more costly measures, such as solid wall insulation, are no longer cost effective.

As described in previous sections, there is great uncertainty in trying to consider cumulative savings from so called "alternative" measures. However, the conservative estimates adopted at every other step of the process so far, could possibly offset overestimation arising from these interactions ; and considering the effect of alternative fuel mix and emission factors, the uncertainty involved is certainly comparable to that introduced by many other factors in the modelling process. Any estimates produced by modelling exercises such as this should be taken as indicative and a way of evaluating the effect of different factors on potential scenarios rather absolute predictors of scenario outcomes. In this context, a trend for cumulative emission reductions from all the measures discussed has been included in the following.

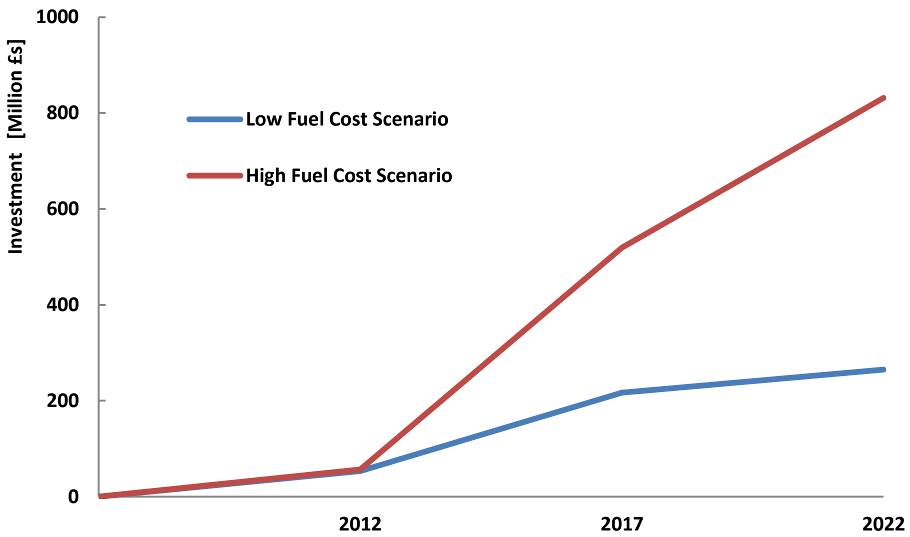

Figure 22: Cumulative upfront investment in cost effective measures in Wales for the high and low fuel cost scenarios.

Figure 23 and Figure 24 shows the contribution to CO_2 emission savings for the Welsh local authorities, and the overall reduction target by the implementation of cost effective measures for the high and low fossil fuel cost scenarios. CO_2 emissions by end user for the Welsh local authorities in 2010 were 7520kt [43, 44]. Comparison at the end user level is more appropriate than reviewing emissions at source, because the savings examined include emissions from the consumption of electricity. Additionally, emissions from the consumption of electricity in the residential sector have been included in the reduction targets set by the Welsh Government [45]. The savings from the measures modelled in the high fuel cost case study amount to 8.8% of domestic emissions at end user level for the region, while the savings for individual local authorities range between 5.5% Flintshire and 10.6% for The Vale of Glamorgan. The potential reduction in annual emissions amounts to about a quarter of the policy target set for the domestic sector. The overall reduction potential is lower in the low fuel cost scenario, at 5.7% of the 2010 emission levels; a reduction which is disproportional to the much lower cost of the measures implemented. This reflects the fact that measures which are easy and very cost effective to implement are put in to practice in both scenarios. Cost increases provide incentives for further measures which are not as cost effective, so after a certain threshold the incremental reductions in CO_2 emissions come at a much higher cost.

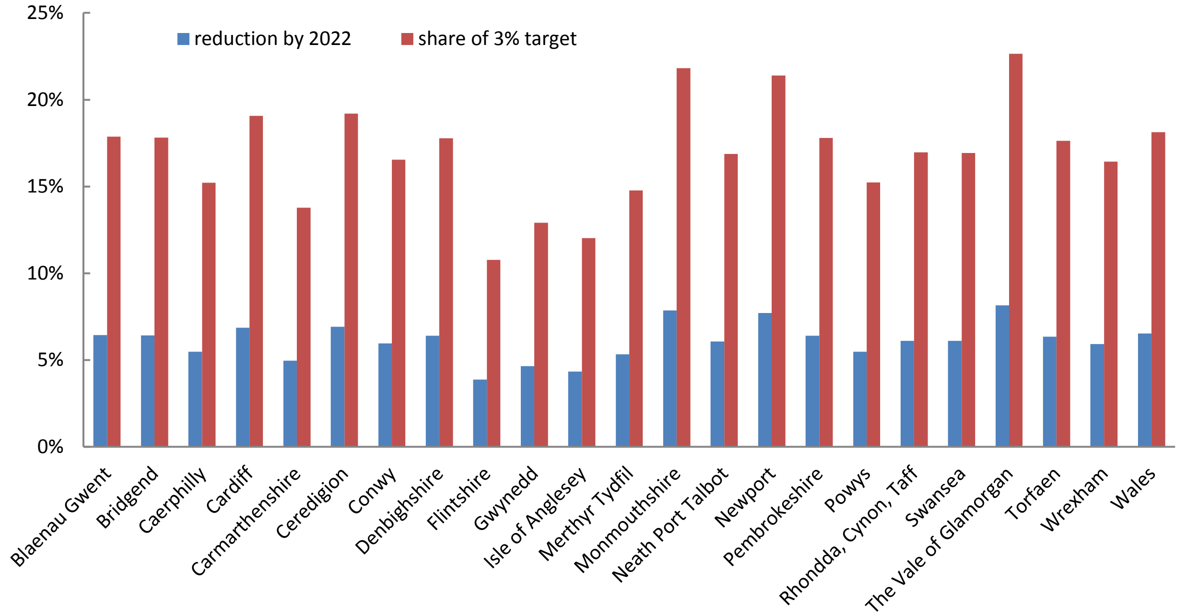

Figure 23: Emission reduction in the domestic sector by cost-effective fabric and systems measures.

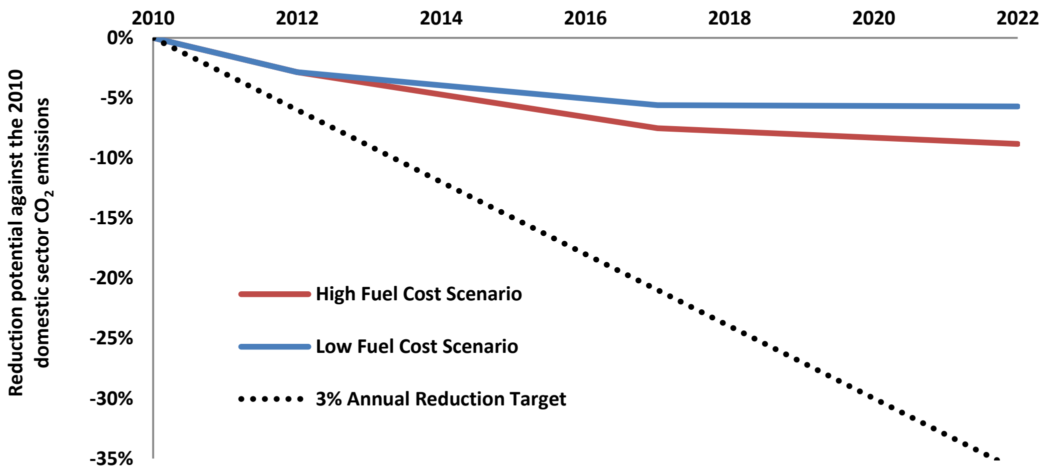

Figure 24: Contribution to CO_2 emission savings for Wales, against the policy target (assuming the target is applied uniformly across all sectors).

6 DISCUSSION AND FUTURE WORK

The aim of the methodology applied was to look into the potential for cost effective energy and carbon saving measures at the city region scale, taking into account characteristics and constraints in each locality. First results indicate that compositional downscale using statistical information at the local authority level can provide useful insights about the retrofit needs and potential at this level.

Assumptions regarding the residential fuel mix and electricity emission factors have a considerable impact on determining the cost effectiveness of measures and the potential CO_2 savings. The effect is exaggerated for local authorities that have a fuel mix markedly different from the assumed average, and becomes more pronounced in general for long term projections, as the uncertainty over the emission factors from power generation increases for future years. Although a first attempt has been made to tackle these issues, providing valuable insights at the regional level, it is clear that they should be subject to further research.

The flexibility of the model in terms of considering different discount rates, fuel prices and carbon emission factors means that different scenarios can be explored to provide feedback for policy support at the local level. The analysis presented mostly refers to a single set of economic parameters – high fuel costs and a discount rate of 7%. Any change in these parameters will have an effect to the potential for CO_2 reduction that can be achieved cost effectively. Note that the relative price of gas, oil, electricity and solid fuels within each scenario is equally as important as the absolute values in defining cost-effectiveness in areas where the fuel mix is more varied.

Almost 9% of the emission reduction required to achieve the overall 3% target set by the Welsh Government; or around a 18% of the same target (if applied uniformly at all sectors) for the residential sector can be achieved by the measures examined in this study, but significant investment, and swift action is needed to achieve this potential. Building fabric measures are the most expensive interventions but also deliver the greater savings. Over 900 thousand such measures could be retrofitted cost effectively in the Welsh local authorities under the high fuel cost scenario examined.

As with any modelling approach, there are limitations in the methodology applied in this study, as well as potential improvements to its application. All considerations and caveats expressed in the methodology behind the CCC data employed, as analysed in the relevant literature [6, 25, 27, 28] still apply.

The study has only considered certain measures, based on current technologies and not all potential measures that are likely to contribute to savings. There is therefore scope to update and improve the list of measures to account for the potential that may arise from future technology developments. As developments in the residential sector accelerate, the model would benefit from a periodic review of the cost data to ensure that they reflect the cost effectiveness of the different measures and policies active at any given time.

Similarly the uptake of different technologies is based on technology curves that had incorporated historical data and policy influences up to the time of the original studies but would need to be updated to reflect progress in measure implementation and the impact of the latest policy decisions.

Many of the measures can be downscaled, but not adjusted to reflect regional needs because the data and methodology are not available, so there is an opportunity to enhance the capabilities of the model in this respect.

The HEED, used for the compositional downscale, contains 50% of the residential stock in Wales, but the coverage of characteristics relevant to some of the measures is much smaller. There is always the risk that a small statistical sample could skew the results if it is not representative. The local authority housing surveys – where available – provide an opportunity to evaluate the picture of the stock as presented through HEED and improve the statistical input for the model. Work in progress on statistical data assessment and cross-referencing indicates that older properties may be under-represented in HEED [19]. Because of that, or due to the focus of the database in registering energy efficiency measures, the condition of the stock may be worse in terms of efficiency than the sample in HEED. For example, the share of properties with uninsulated walls appears much higher in certain local authority housing condition surveys than what is recorded in HEED. The differences in the timing and format of the local authority condition surveys do not allow their direct use as input in the model, and any modification of the HEED data has to be carefully studied.

It would be of interest to evaluate the results obtained through the model to benchmark performance and examine whether there is a need to calibrate and develop the existing structure further to better reflect regional characteristics. The Welsh School of Architecture has detailed statistics and modelling work for Neath Port Talbot [21, 46] which can be used to benchmark model performance, and the effect of the use of aggregated statistics in general and the HEED in particular.

Modelling the residential sector on the basis of an average property and accounting for the cumulative effect of certain measures has inherent uncertainties. An evaluation can also be performed on how representative the "average" house type used in the model is, against different property types prominent in the Welsh housing stock in terms of the savings quoted for each measure. This could be achieved by comparing the model data with data generated by the SAP Sensitivity Tool for selected property types [47]. Additionally the reductions arising from measure interactions could be further assessed against the factors already employed in the calculation.

The present work has sought to reconcile the need to incorporate regional characteristics in broad top-down scenario work, with the reality of data and resource scarcity which does not allow detailed bottom up models to be implemented for most areas. It is essential to reconcile these approaches and work towards an accurate portrayal of the sector in order to address residential stock-specific constraints and opportunities. In doing so, mid-way approach using elements from both top-down and bottom-up models may have to be devised to address the needs of users at the regional and local authority level.

7 ACKNOWLEDGEMENTS

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