INVESTIGATING CO_2 EMISSION REDUCTIONS IN EXISTING URBAN HOUSING USING A COMMUNITY DOMESTIC ENERGY MODEL

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ABSTRACT

This paper presents the development of an energy and carbon model of existing dwellings and its application to urban housing. The model is used to predict the energy use and CO_2 emissions of the housing stock of the city of Leicester, UK, and to estimate the effect of energy efficiency interventions. It is shown that a high level of energy efficiency interventions has the potential to reduce overall CO_2 emissions by around 41%. The model methodology is discussed and potential improvements are explored.

INTRODUCTION

On the 26th November 2008 the UK Government published the Climate Change Bill which commits the UK to at least an 80% reduction in CO_2 emissions by the year 2050 compared to 1990 levels (DEFRA, 2008). The Committee on Climate Change set out in its December 2008 report 'Building a low-carbon economy' carbon budgets for the next three 5-year time periods (CCC, 2008). The report recommends that by 2020, UK CO_2 emissions should be reduced by 34% to 46% of 1990 levels if the 2050 target is to be met. These reduction targets are challenging and will only be met by a step-change in energy efficiency across all sectors of the UK economy.

The energy use in housing accounts for around 25% of the total UK CO_2 emissions (DEFRA, 2007). Housing is a difficult sector to change as domestic buildings have a long life, many are privately owned and there is a great variation of different built forms types and ages in the stock. However, it is widely accepted that emissions from housing will need to be reduced substantially by 2050 if national targets are to be met. This will require significant changes to the current housing stock and the ways in which householders currently use energy in their homes.

The UK Government has introduced the Code for Sustainable Homes (DCLG, 2008) and other planning guidance that aims to ensure that all dwellings built after 2016 will be zero-carbon. This zero-carbon status refers to the energy consumption during the habitation of the building and may include off-site zero-carbon energy generation. Therefore, the future CO_2 emissions of the housing stock are likely to consist largely of the emissions from dwellings already constructed. It is this existing housing where large reductions in CO_2 emissions need to take place.

This paper presents the development of an energy and carbon model which makes predictions for communities of existing dwellings. The Community Domestic Energy Model (CDEM) is based on the steady state energy model BREDEM-8, the Building Research Establishment Domestic Energy Model version 8 (Anderson et al., 2002). Census data and other national surveys are used to define discrete dwelling archetypes, which together represent the community's stock: CDEM currently uses 47 such archetypes based on built form type and age band.

In this work CDEM is used to predict the energy use and CO_2 emissions for the housing stock in the City of Leicester, UK, as part of the EPSRC-funded project Measurement, Modelling, Mapping and Management (4M): An Evidence-Based Methodology for Understanding and Shrinking the Urban Carbon Footprint (4M, 2009). Predictions for the existing Leicester housing stock are presented and the effect of energy efficiency interventions to reduce CO_2 emissions are investigated. The limitations of the steady-state modelling approach and the routes to improving the model are discussed.

MODELLING METHODOLOGY

A schematic of the modelling process is shown in Figure 1. The model is physically based and works by estimating the heat losses, internal temperatures and energy flows in the dwellings. This allows the effects of measures which change the physical properties of a dwelling (such as increased insulation and improved heating system efficiencies) to be predicted. The model makes predictions for communities of dwellings which includes wards, local authorities, regions and the national housing stock by, broadly stated, combining, in the correct proportions, predictions for the 47 dwelling archetypes.

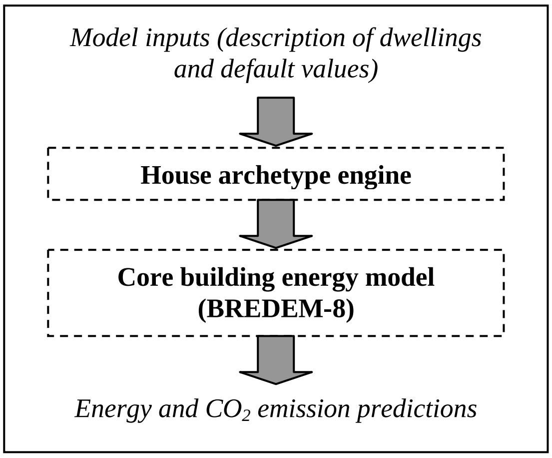

Figure 1: Schematic of the CDEM modelling process

The UK industry standard tool for making energy predictions in individual dwellings is the Building Research Establishment Domestic Energy Model (BREDEM), which actually comprises of a suite of models which make annual or monthly energy consumption predictions to various degrees of detail (Anderson et al., 2002). BREDEM is a physically based model which requires detailed information on the dwelling to estimate the energy consumption of four end use categories: space heating; water heating; cooking; and lights and appliances. It has an extensive history of testing and validation (Dickson et al., 1996) and is used in many applications including the UK Government's Standard Assessment Procedure (SAP) for dwellings (DEFRA, 2005). In this work the calculation algorithms of BREDEM-8, a version of the model which makes monthly energy predictions, are used.

CDEM is designed around the assumption that the distribution of energy use of English dwellings can be simplified by separating the dwellings into particular categories. This approach means that energy predictions are made for each category of dwelling rather than for each individual dwelling in the community under study (which greatly simplifies the modelling process as large communities such as regions can contain millions of dwellings). The technique has been established in previous domestic energy modelling work (Hinnells et al., 2007, Johnston et al., 2005, Shorrock and Dunster, 1997).

Here the dwelling categories are referred to as house archetypes and each house archetype can be thought of as a notional dwelling which represents an average dwelling within its category description. For example, the house archetype of a semi-detached house built from 1945 to 1964 represents a notional dwelling which describes the average characteristic of all 1945 to 1964 semi-detached houses in the community. Energy predictions are made for this notional dwelling and the results are multiplied by the number of dwellings of this archetype in the community to give an overall prediction figure. Thus the energy consumption for a community of dwellings is given the following equation:

$$E_{COM} = \sum_{i=1}^{n} E_i \times N_i$$

where E_{COM} is the overall predicted energy consumption for a community of dwellings (kWh), n is the total number of house archetypes, E_i is the predicted energy consumption for the notional dwelling of house archetype i (kWh),and N_i is the total number of dwellings of house archetype i in the community.

Space heating in dwellings represents the majority of domestic energy consumption and therefore it is important that predictions of space heating energy use are accurate. The house archetypes in CDEM were chosen to capture the variation in space heating in the housing stock. Built form is a key determinant of space heating as the type of dwelling (such as detached, semi-detached, terrace etc.) determines the number of exposed walls and the average floor area of the average dwelling, both of which affect the dwelling heat loss. The age of the dwelling is also a key determinant as older buildings are constructed to lower thermal standards (for example using solid walls, unfilled cavity wall and single glazing) than modern buildings which again strongly affects the heat loss. The house archetype were based on the combinations of built form and dwelling age. Pre-1900 purpose built flats and post-1945 other flats were not considered as these combinations occur very infrequently in the housing stock. The 47 individual house archetype chosen are defined in Table 1.

Table 1: House archetype category combinations

Built form categories	Dwelling age band categories
End terrace, mid terrace, semi detached, detached	pre 1850, 1851 to 1899, 1900 to 1918, 1919 to 1944, 1945 to 1964, 1965 to 1974, 1975 to 1980, 1980 to 1990, 1991 to 2001
Flat: purpose built	1900 to 1918, 1919 to 1944, 1945 to 1964, 1965 to 1974, 1975 to 1980, 1980 to 1990, 1991 to 2001
Flat: other (converted or in commercial building)	pre 1850, 1851 to 1899, 1900 to 1918, 1919 to 1944

Each house archetype was populated with data from a variety of sources. The 2001 English House Condition Survey (EHCS) (DCLG, 2007) was used to determine average properties, such as average floor area and average number of occupants, within each house archetype. Some properties, such as the type of heating systems in use, could not be expressed as an average value. In such cases the distribution was used as a input to the model, for example 1945 to 1964 semi-detached houses were recorded as having a heating system distribution including 49% gas single purpose central heating, 32% gas back boiler central heating and 4% electric storage heaters. In this case the model makes calculations for each heating system type, and then combines the results in proportion using weighted averages. Values in the BREDEM default tables, such as wall U-values, were used with English House Condition Survey data to estimate the average thermal properties of the building materials in each house archetype.

The geometry of the dwellings, which determines such properties as exposed wall area and glazing area, was defined using previous work (Allen and Pinney, 1990) and using reference tables in SAP 2005 (DEFRA, 2005). The English House Condition Survey did not include data on the proportion of low energy lighting or the distribution of cooker type and information from the Market Transformation Programme (MTP) was used to derive estimates for these values (MTP, 2007). Further, model inputs included the number of dwellings for each built form, derived from Census 2001 data (ONS, 2001), and average monthly external air temperature (MET Office, 2007). As an example, an estimation of the overall level of various energy efficiency interventions present in the 2001 Leicester housing stock, based on these national surveys and datasets, is shown in Table 2. These can be broken down to give the level of intervention for each archetype.

Table 2: Levels of energy efficiency interventions estimated for the Leicester housing stock in 2001

Energy efficiency intervention	**Level of intervention in housing stock**
Solid wall insulation	1% of dwellings[1]
Cavity wall insulation	31% of dwellings
Gas condensing boilers	5% of dwellings
Double glazing	61% of dwellings
Average air tightness	0.7 ach
Average loft insulation thickness	98mm
Average hot water tank insulation thickness	30mm
Hot water tank thermostat	58% of dwellings
100% low energy lights	3% of dwellings

[1] There were 115,751 dwellings present in Leicester in 2001

MODEL VALIDATION

The BREDEM algorithms used in CDEM were validated against the results of two previous BREDEM-8 implementations. In each case the CDEM energy predictions compared well with those of the previous work (Gasden, 2001 and Seale, 1993). An initial validation step was to evaluate the predictions of dwelling heat loss, the heat energy flow through the building envelop where there is a 1K temperature difference between internal and external temperatures. The predicted dwelling heat losses for the detached house archetypes, as defined by the national survey datasets, are plotted against average total floor area in Figure 2. Heat loss shows an approximate linear relationship with floor area, which is as expected as the dwelling heat loss will increase with the size of the building. The older buildings have high heat losses due to larger floor areas (which infers a large building envelop area) and low U-values (due to poor insulation and use of construction techniques such as solid wall and unfilled cavity walls). The dwelling heat losses decrease in later buildings as materials and construction improve and building size becomes smaller. There is a noticeable increase in the average floor area of detached houses built in the 1900 to 1918 period but the heat loss does not increase due to increased use of cavity wall construction in this period. The average floor area of post-1975 detached houses remains relatively constant and actually increases slightly in the 1990s. Despite this the dwelling heat loss continues to decrease in post 1975 houses and this clearly demonstrates the effects of higher thermal standards of building regulations on modern housing.

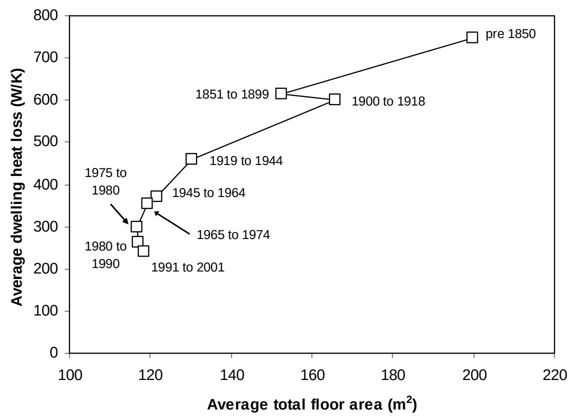

Figure 2: Average total floor area against predicted average dwelling heat loss for the detached house archetypes

An external dataset was used to validate the CDEM energy consumption predictions for the house archetypes. The 1996 English House Condition Survey gathered gas and electricity meter readings over a two year period from around 3,600 dwellings (DCLG, 2007). This provided sufficient data to calculate energy consumption statistics (the mean and the 95% confidence intervals for the mean) of the different built form types. Average monthly climate data for England from 1996 to 1998 was used to generate a comparison set of CDEM energy predictions. The predicted and measured annual gas consumption in England for each built form type compare well in the majority of cases (Figure 3). CDEM predictions for mid terrace, semi-detached and purpose-built flats are slightly below the lower 95% confidence interval boundary for English House Condition Survey measurements. This may indicate a combination of inaccuracies in the modelling process and assumptions and the effects of sampling and measurement errors in the English House Condition Survey measurements.

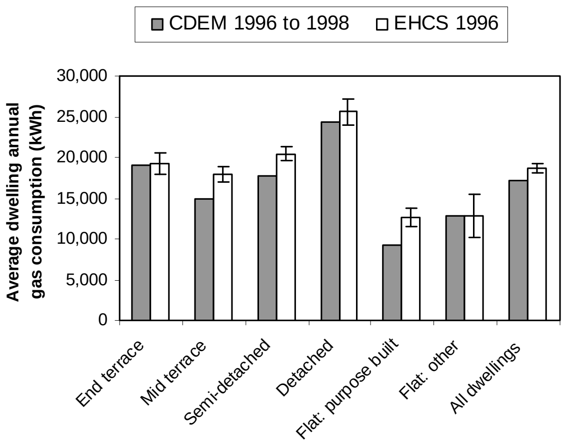

Figure 3: CDEM predictions of annual gas consumption in England by built form type compared to the English House Condition Survey (EHCS) 1996 measurements. The bars represent the 95% confidence intervals for the EHCS data.

CDEM energy predictions for the city of Leicester were compared against the measured average dwelling gas, electricity, oil and solid fuel consumption for 2005as given by the Department of Business, Enterprise and Regulatory Reform (BERR) regional statistics (BERR, 2008). The CDEM predictions of the average dwelling annual energy consumption for the four fuel types, made using 2004 East Midlands climate data, are compared to the BERR regional statistics values in Figure 4. The CDEM predicted annual gas consumption is slightly below the BERR value (by -6.7%) and the predicted electricity consumption shows a good comparison (a 0.3% difference). Both the CDEM predicted oil and solid fuel consumption, although only a minimal proportion of the average dwellings' energy use, are significantly higher than the measured BERR data. This may be due to the DTI measurements reporting only coal and manufactured solid fuel consumption and not other solid fuels such as wood. Also as the house archetypes are based on national surveys this may represent the difference between the national housing stock and the urban housing stock of the city of Leicester. However oil and solid fuel are estimated to account for around only 8% of overall CO_2 emissions in dwellings so this overestimation will not unduly affect the analysis results.

The comparison between CDEM predictions for gas, electricity and oil and the BERR data values provides confidence in the modelling process. The 1996 English House Condition Survey and BERR comparisons could be improved by altering the modelling assumptions such as geometry descriptions, space heating patterns and calculation algorithms. However this is not attempted here as there is no sound basis for such an approach based on the available known characteristics of the housing stock. Instead the results from ongoing domestic building surveys and field measurements, when they become available, will provide much of the additional information required and these will be used to improve the model predictions.

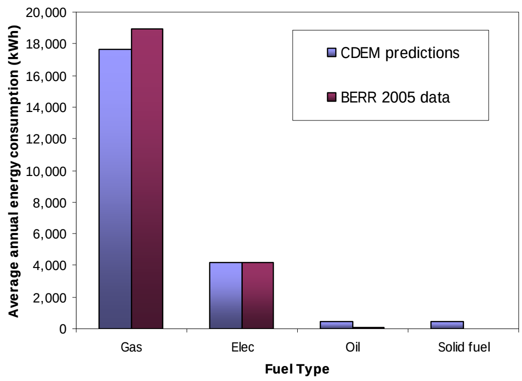

Figure 4: Average dwelling energy consumption by fuel type for Leicester as given by CDEM predictions and BERR 2005 data

RESULTS

Annual energy use and carbon emissions

Predictions for the energy consumption and CO_2 emissions for the 2001 Leicester housing stock were made using 1971 to 2000 average climate data so the results would not be skewed by the weather patterns of one particular year. The CO_2 emissions of different fuels are calculated using standard conversion factors (Carbon Trust, 2006). The energy consumption and CO_2 emission predictions for the house archetypes are summarised for the six built form types in Table 3. The energy consumption predictions are broken down by fuel type and the CO_2 emission predictions by fuel type and by end use. Descriptive statistics of the numbers of built form types, average dwelling heat losses and average annual internal temperatures are also given. The CO_2 emissions of the average Leicester dwelling, based on the 30 year average climate data, is predicted to be 5.4 TCO_2.

Table 3: CDEM energy and CO_2 emission predictions by built form type for the 2001 Leicester housing stock based on 1971 to 2000 climate data

		End terrace	Mid terrace	Semi-detached	Detached	Flat: purpose built	Flat: other	All dwellings
Number of dwellings (thousands)		10.2	30.7	42.9	11.8	14.5	5.5	115.8
Average dwelling total floor area (m^2)		80.0	77.2	83.5	130.5	57.1	67.6	82.2
Average number of occupants		2.72	2.77	2.69	2.66	1.80	1.96	2.56
Average dwelling heat loss (W/K)		271	226	262	383	134	207	247
Average annual internal temperature (°C)		18.0	18.3	18.1	18.0	19.4	18.7	18.3
Average annual energy consumption (MWh) and % of total by fuel type	**Gas**	19.8 81%	16.3 79%	18.8 78%	25.7 74%	9.9 71%	16.1 77%	17.7 77%
	Electricity	4.1 17%	4.1 20%	4.1 17%	4.8 14%	4.0 29%	4.5 21%	4.2 18%
	Oil	0.1 0%	0.0 0%	0.3 1%	3.2 9%	0.0 0%	0.2 1%	0.5 2%
	Solid Fuel	0.4 2%	0.2 1%	0.7 3%	1.03 3%	0.0 0%	0.2 1%	0.5 2%
Average annual CO_2 emissions (TCO_2) and % by fuel type	**Gas**	3.8 66%	3.1 63%	3.6 63%	4.9 60%	1.9 52%	3.1 60%	3.4 62%
	Electricity	1.8 31%	1.8 36%	1.8 32%	2.1 26%	1.7 48%	1.9 38%	1.8 33%
	Oil	0.0 0%	0.0 0%	0.1 2%	0.8 10%	0.0 0%	0.0 1%	0.1 2%
	Solid Fuel	0.1 2%	0.0 1%	0.2 4%	0.3 4%	0.0 0%	0.1 1%	0.1 3%
Average annual CO_2 emissions (TCO_2) and % by end use	**Space heating**	3.0 52%	2.2 45%	2.9 51%	5.0 62%	1.4 39%	2.8 54%	2.7 50%
	Water heating	1.2 20%	1.2 23%	1.2 21%	1.2 14%	1.0 27%	1.0 20%	1.1 21%
	Cooking	0.3 5%	0.3 6%	0.3 5%	0.3 3%	0.2 7%	0.3 5%	0.3 5%
	Lights and appliances	1.3 23%	1.3 26%	1.3 23%	1.6 20%	1.0 27%	1.1 21%	1.3 23%
Average annual total CO_2 emissions (TCO_2)		5.7	4.9	5.6	8.1	3.6	5.1	5.4
Average annual total CO_2 emissions per unit floor area (TCO_2/m^2)		0.071	0.064	0.068	0.062	0.063	0.076	0.066
Average annual total CO_2 emissions per occupant (TCO_2)		2.1	1.8	2.1	3.0	2.0	2.6	2.1

Detached houses have the largest CO_2 emissions (8.1 TCO_2) followed by end terraces (5.7 TCO_2) and semi-detached houses (5.6 TCO_2). Purpose-built flats have the lowest CO_2 emissions (3.6 TCO_2). The distribution of CO_2 emissions for all dwellings from end use consumption is: space heating 50%; water heating 21%; cooking 5%; and lights and appliances 23%. Detached houses have the largest space heating CO_2 emissions (5.0 TCO_2) and lights and appliances CO_2 emissions (1.6 TCO_2), due to the high dwelling heat loss and large total floor area. The high number of occupants in semi-detached houses, together with a high consumption of solid fuels, means that this built form type has the highest CO_2 emissions from water heating (1.15 TCO_2). Mid terraces have the highest cooking CO_2 emissions (0.28 TCO_2), again due to the high number of occupants. The consumption of gas at the dwellings accounts for 77% of all energy consumption but only 62% of CO_2 emissions. This is an effect of the relatively low carbon intensity of gas compared to the other fuels. Similarly electricity, with its high carbon intensity, accounts for 18% of overall energy consumption but 33% of CO_2 emissions. The percentage of CO_2 emissions from oil consumption (2%) and sold fuel consumption (3%) represents a small proportion of overall CO_2 emissions. The total annual CO_2 emissions per occupant are highest in detached houses (3.0 TCO_2 per person) and are lowest in mid terraces (1.8 TCO_2 per person). The combination of relatively high CO_2 emissions and low occupancy means the other flats have the second highest per person CO_2 emissions (2.6 TCO_2 per person).

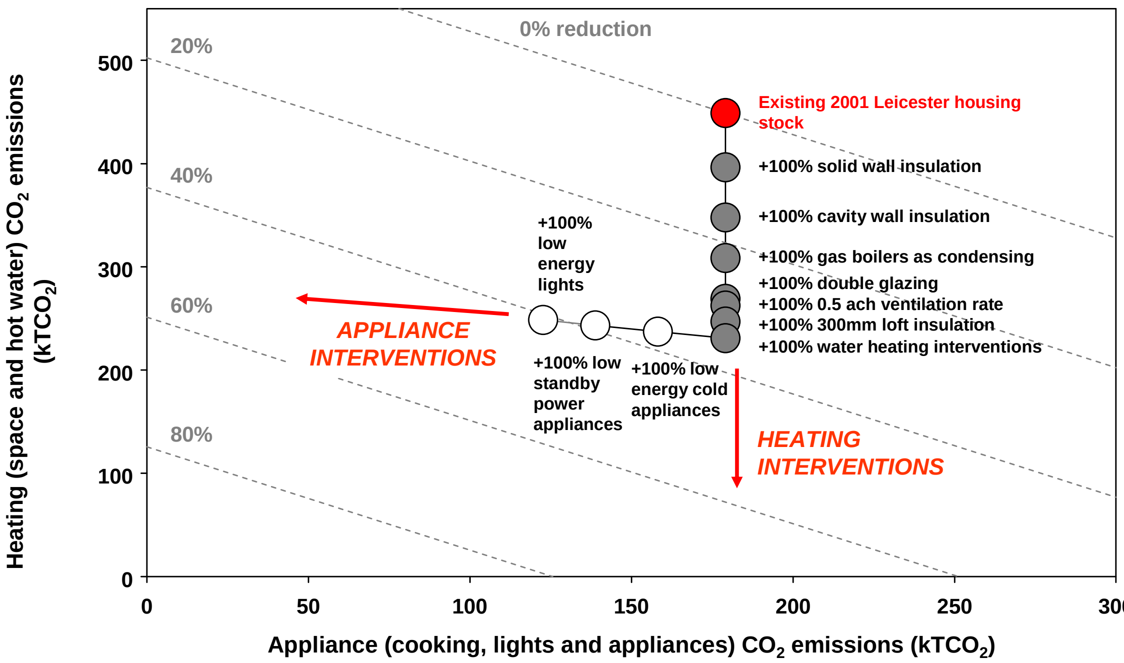

Figure 5: Predicted reductions for appliance and heating CO_2 emissions for the Leicester 2001 housing stock based on 1971 to 2000 climate data

Energy efficiency interventions

The effects of energy efficiency measures on dwelling CO_2 emissions were investigated by altering the input data to the model for each house archetype. The new specifications of the upgraded dwellings were determined using the input datasets to the model and would depend on the dwelling archetype. For example, cavity wall insulation for the 1945 to 1964 semi-detached dwelling archetype would increase the wall U-value from 1.0 W/m^2K to 0.5 W/m^2K (based on figures from the SAP - Defra, 2005). Different figures would apply for other age bands and other built form types. To investigate the effects of cavity wall insulation on, say, 1945 to 1964 semi-detached dwellings the percentage of dwellings within this house archetype which have cavity wall insulation is altered from its original value of 36% to 100%.

Energy efficiency measures were divided into two distinct categories: heating energy efficiency measures which reduce CO_2 emissions of space heating and hot water heating; and appliance energy efficiency measures which reduce CO_2 emissions of cooking, lights and appliances usage. To illustrate this, the predicted average dwelling annual CO_2 emissions for all Leicester dwellings is shown in Figure 5 with the appliance (cooking, lights and appliances) CO_2 emissions plotted against the heating (space and hot water) CO_2 emissions.

For existing 2001 Leicester housing stock the appliance CO_2 emissions (179.1 $kTCO_2$) and the heating CO_2 emissions (449.0 $kTCO_2$) give a total CO_2 emission figure of 628.0 $kTCO_2$. The dashed lines on the figure show contour lines representing the locations of potential CO_2 emission reductions. For example, in order to reduce overall dwelling CO_2 emissions by 60% or below the predicted value the CO_2 emissions for all dwellings must move its location to a position below the 60% contour line.

The cumulative effects of heating and appliance energy efficiency measures are shown in Figure 5. The energy efficiency measures were chosen to illustrate the maximum CO_2 emission reductions possible through these types of interventions. For example it was assumed that all solid wall dwellings are insulated (shown as '+100% solid wall insulation'). The order of heating energy efficiency was based on the amount of CO_2 reductions achieved with the largest reducers applied first. The heating measure with the most potential to reduce CO_2 emissions is solid wall insulation with a 8% overall reduction if applied to all dwellings with solid walls. Water heating energy efficiency measures (which included improving hot water cylinder insulation levels and the presence of cylinder thermostats) had the lowest impact on CO_2 emissions with a 3% reduction. It should be noted that energy efficiency measures which improve the efficiency by which fuel is used in a dwelling, such as upgrading all gas boilers to condensing boilers, will have more impact if applied before insulation measures (as a larger amount of fuel is consumed) than after insulation measures have been installed. The analysis shows that by implementing all possible heating energy efficiency measures the overall heating CO_2

emissions are reduced from 449.0 kTCO2 to 230.8 kTCO2 and overall CO_2 emissions are reduced by around 35% of the original 2001 housing stock value.

The effects of appliance energy efficiency interventions (by replacing appliances with low energy versions) are also shown in Figure 5 as following on from the heating measures. The CO_2 emission reductions for low energy cold appliances (such as fridges and freezers) and low standby power appliances were estimated from previous work investigating household appliance energy usage in a sample of 72 UK dwellings (Firth, 2008). The combined effect of low energy cold appliance, low standby power appliance and low energy lights reduced the appliance CO_2 emissions from 179.1 $kTCO_2$ to 122.6 $kTCO_2$. However the reduction in electricity consumption caused the internal heat gains from electrical appliances to decrease and so the heating CO_2 emissions increased slightly (from 230.8 $kTCO_2$ to 248.6 $kTCO_2$) to compensate for the lower internal heat gains. This additional heating requirement lowered the effect of the appliance energy efficiency measures on overall CO_2 emissions. The combined effect of the heating and appliance measures reduced overall Leicester housing stock CO_2 emissions by around 41% of the 2001 value, only 6% more than the reduction for heating energy efficiency measures alone (35%).

DISCUSSION

The analysis presented in this work demonstrates the potential of energy efficiency measures to reduce CO_2 emissions in dwellings. The results are based on a combination of survey data, standard assumptions and energy modelling which do not attempt to present a complete picture of the variation of energy use in homes but rather to give a succinct illustration of the potential effects of strategies to reduce CO_2 emissions. It is recognised that some assumptions, such as internal demand temperatures and heating patterns, do not adequately capture the variation in the housing stock at present and results from the field studies in the 4M project will be used to improve these inputs to the modelling process. Some modelling complexities, such as the possibility of 'take back factor' or 'comfort factor' (due to increased internal temperatures resulting from energy efficiency measures), are also not adequately represented in the current modelling process but results from ongoing field measurements of such processes will be used to update the model algorithms.

The use of a steady-state model as the core building energy model has a number of limitations. There are a number of low carbon technologies which can be used to reduce heating CO_2 emissions in dwellings, such as solar thermal systems, combined heat and power systems, heat pumps and district heating schemes. To adequately simulate the effectiveness of these energy systems, installed into individual dwellings and communities of dwellings, a dynamic modelling approach is needed. For CDEM, dynamic predictions could be achieved by substituting the current steady-state core building energy model (BREDEM-8) with a dynamic thermal model. An alternative is to develop estimates of the energy and carbon savings resulting from such measures using field measurements and dynamic thermal models and then derive simpler models, that can be embedded into BREDEM-8, which produce monthly energy and CO_2 reduction estimates.

The use of the house archetypes means that number of predictions are limited to a selection of average house types. However in the housing stock there may be particular target groups (for example very large detached houses or particular types of households) where certain interventions would be most effective. The house archetype approach simplifies the variation observed in dwellings and so potential house or household characteristics of interest may be overlooked. There is also a need to more accurately model the behaviour of the occupants in their homes and their influence on energy consumption. Steps to model occupant behaviour, using Bayesian belief networks, are being made in the Carbon Reduction in Buildings project (CaRB, 2009) and the resulting algorithms will be incorporated into CDEM. Incorporating the costs of energy efficiency interventions, allowing a cost-benefit analysis for target house and household types, is also being explored.

Finally the effect of uncertainty on the model predictions is an area of further work. Initial work has been undertaken using local sensitivity analysis to investigate the influence of the model input parameters on the output predictions. From such sensitivity analysis it may be possible to develop very simple planning tools to assist with the accurate targeting of energy efficiency policies.

CONCLUSION

This work has described the development of a new model, the Community Domestic Energy Model (CDEM), to predict energy consumption and CO_2 emissions in dwellings. The CDEM modelling methodology has been described and the model predictions have been validated against external measurements. Energy consumption and CO_2 emission predictions for the existing 2001 Leicester housing stock have been presented based on 1971 to 2000 average climate data. The predictions are made using 47 house archetypes, unique dwelling types based on the built form type and the dwelling age. The effects of potential energy efficiency measures have been estimated and discussed. Key conclusions are:

- The average dwelling annual CO_2 emissions for the Leicester housing stock was calculated as 5.4 TCO_2.

- The maximum potential for heating energy efficiency interventions was estimated as a 35% reduction in CO_2 emissions (based on 2001 levels). Appliance energy efficiency interventions were predicted to give a further reduction of 6% in CO_2 emissions.

The potential to improve the model predictions through dynamic thermal models, occupancy modelling and sensitivity analysis has been discussed. This work is ongoing and current household surveys and monitoring studies underway in the 4M project will be used to improve the inputs to the model (in particular the inputs for the Leicester housing stock), to improve the model algorithms and to further validate the model predictions. In particular the realistic CO_2 redu tions, rather than the poential, will be investigated further.

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