

A SAP SENSITIVITY TOOL AND GIS-BASED URBAN SCALE DOMESTIC ENERGY USE MODEL

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ABSTRACT

This paper introduces a new approach to predicting domestic energy use on an urban scale and is based on a method of applying sets of results from a SAP (UK's Standard Assessment Procedure) sensitivity tool (WSA 2013) to an area, using and extracting data from a Geographical Information System (GIS). It is demonstrated for the Cardiff Local Authority (LA) area (approximately 140,000 dwellings) and is validated by comparison with the Department of Energy and Climate Change's (DECC) data on actual residential gas and electricity consumption per UK census area (DECC 2010). The method concludes by applying results from the validation to modify variables and assumptions in the SAP sensitivity tool in order to better reflect consumption patterns in UK households.

INTRODUCTION

The domestic stock is directly responsible for 27% of the UK's total emissions and it is predicted that $\frac{2}{3}$ of the existing stock will still be standing in 2050 (Forseight 2008). Reducing emissions from existing dwellings is therefore crucial to the success of the UK government's 2050 target to cut greenhouse gas emissions by 80% (DECC 2009). There is also a growing recognition that action by Local Authorities will be critical to the achievement of this target (DECC 2009). National Indicator 186 requires each Local Authority to publish figures on carbon emissions yearly, including emissions from housing (DECC 2009). This is an enormous challenge for Local Authorities due to the lack of consistent publically available tools and methods for calculating the potential carbon savings (Urge-Vorsatz 2007; DECC 2009). This need by local governments is also acknowledged by (V. Cheng 2011) who identifies that current UK models are evaluated at national level and therefore could become speculative on disaggregated levels (e.g. cities, regions and Local Authorities).

Domestic bottom-up models attempt to estimate baseline energy consumption by applying quantitative data to representatives of the housing stock. They are expected to be capable of assessing

and identifying suitable measures to reduce energy consumption on a large scale. (Firth 2010) highlights the potential of constructing simpler models with only a set of limited input parameters and associated sensitivity coefficients. Moreover (M. Kavgić 2010) emphasises that the transparency of data sources and model structures is a crucial issue for their future use.

This paper attempts to outline a transparent method based on a simple tool with a limited set of input parameters. It accentuates variables and assumptions with the greatest significance in terms of energy consumption such as total floor area and indoor temperature set point. The accurate identification of dwellings is also fundamental to the method and although specific to this case study, similar methods and data sources could be used for any UK area. It is hoped that the tool's rapidity and its simple transfer to GIS results in a method that can analyse the effect of adjustments to fabric or system parameters on a regional scale. This along with its transparency and flexibility means that, in future, it could be applied to any number of census areas and could easily be used as a prediction tool for energy efficiency and renewable energy technologies for any area in the UK from neighbourhood to national level.

METHOD

Overview of Method

Cardiff Local Authority area was used as a case study, which included around 140,000 dwellings in total covering 214 Census areas, also known as Lower Super Output Areas (LSOA). The method comprised three main steps: the first analysed data sources relating to the identification and classification of dwellings while in the second, the SAP sensitivity tool was used to calculate the baseline energy demand for the identified classifications. This was based on statistical data relating to the prevalence of fabric and system characteristics. Both sets of data were combined and aggregated to LSOA level using a GIS before initial identification, classification and energy demand results were compared with reliable external sources. The final step builds on the discrepancies found when comparing the energy demand of the model

with actual energy consumption data on an aggregated level (LSOAs). In line with common limitations and issues of domestic energy models identified by others in the field, a first attempt was made to adjust and refine the model. The adjusted model's result was analysed and used to evaluate its capability and identify further work needed to ensure its reliability when approximating the effect of energy efficiency measures on different scales. An overview of the method can be seen in figure 1.

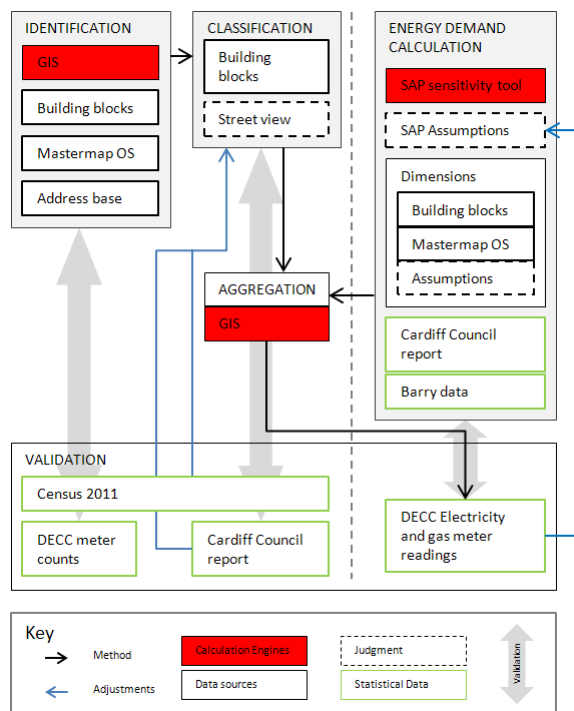


Figure 1: Overview of method

Identification and Classification of Dwellings

The accuracy of dwelling identification was fundamental in creating a reliable bottom-up energy demand model. Furthermore, the data used for classifying the stock needed to be as precise as was practically possible in order to maximise the meaningfulness of the aggregated results. The data sets used were GIS based making it possible to merge the relevant sources to form one data set with all necessary information for the energy demand model. A sample of the three sources used can be seen in figure 2 and were:

- Building Block** (GeoinformationGroup 2013): Each block was categorised into one of five age bands and fifteen typologies with the height of the block representing the rough height of the related buildings, making it possible to approximate the number of storeys
- Master Map Topography Layer** (OrdnanceSurvey 2013): Each polygon's area gave detailed ground floor area for each

separate building

- **Address Base Premium** (OrdnanceSurvey 2013): Each point represented a current Royal Mail postal address with each classed by the use of the address making it possible to identify all residential addresses

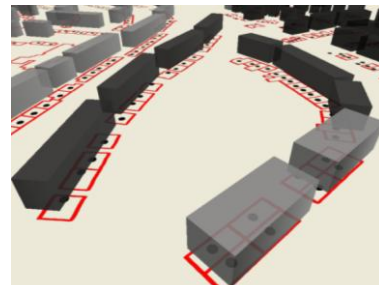


Figure 2: Data sources for the identification and classification of dwellings

Incomplete data

Although the data merged well in general, some problems arose due to inconsistencies in the coverage and creation date of sources. Building block data covers urban areas, therefore 6 of the 214 LSOAs had no classification or height data available. As a consequence they were not included in the case study. Other LSOA had incomplete building blocks data:

1. LSOAs on the periphery of the Local Authority had no data for some of the outer residential buildings, marked as crosses in figure 3
2. LSOAs with large new residential neighbourhoods developed since 2009, highlighted in dark gray in figure 3
3. LSOAs with a significant number of flats in commercial areas; black in figure 3

Three unique classifications relating to typology and age were given to these three groups of addresses so that they could be assigned with appropriate energy use approximations.



Figure 3: points representing residential addresses

A very small number of addresses had missing MasterMap Topography polygons, therefore a default floor area of 90m² was assigned to each. Addresses with missing data accounted for just under 15% of those in the case study area.

Validation

Identification of Dwellings

The merged data set containing details of all residential addresses was the foundation for the model. It appeared to be a reliable starting point as the number of addresses identified in each LSOA agreed well with the number of households per LSOA in the 2011 Census (Statistics 2013). The comparison can be seen in figure 4.

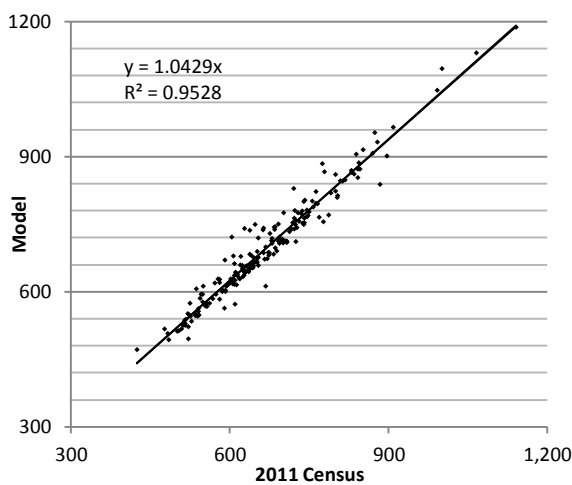


Figure 4: Number of dwellings in Cardiff LSOAs in 2011 census results and in model

Typology Classification

To simplify the process, 15 typologies were reduced to 4, retaining only the core typologies: detached, semi detached, terraces or flats. 2 of the original 15 typologies (semis in multiples of 4,6,8, and planned balanced mixed estates) and one of the newly created typologies (newly built mixed estates) were initially considered to be semi detached. Comparing the distribution of the 4 core typologies with census 2011 data on typologies for the Cardiff Local Authority suggested that this assumption was not just and could lead to inaccurate results. *Google's Street view* and differences in the distribution when compared to Census 2011 data was used to re-categorise these 3 typologies. This can be seen in figure 5 and are the classifications used in the final gas and electricity demand results.

Classification of Age

Very few data sources existed that detailed the age of dwellings in depth. However, two sets of data were used to verify the age classifications and to aid in classifying those with missing data. The Living in Wales survey was conducted in 2008 and gives an

overview of the construction period of dwellings across Wales. Cardiff County Council's private sector stock condition survey conducted in 2005 gives an idea of the distribution specifically within Cardiff Local Authority although it does not represent the full stock (FordhamResearch 2005).

The percentage in each age group from these two surveys along with the mapped data can be seen in figure 6. Over 90% of the unclassified addresses in terms of age are those with missing data. 8% of those (dark gray in figure 3) were assumed to be newly built since 2009 and therefore were easily classified as post 1979. This left a remaining 7% which both surveys suggested to be pre 1919 dwellings. These mostly consisted of dwellings outside the urban area or flats in commercial areas.

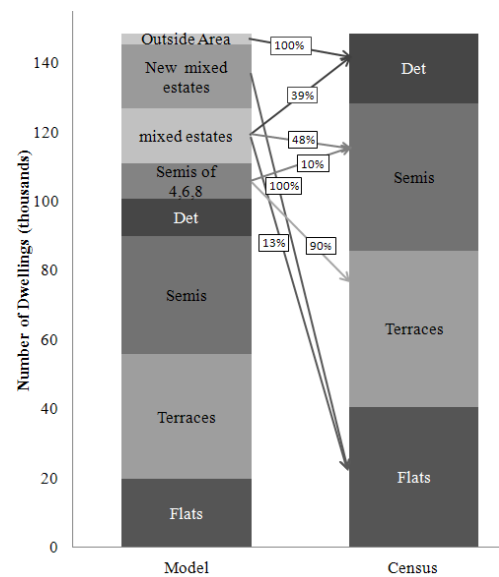


Figure5: Re-categorisation of Semis in multiples of 4,6,8 and mixed estates

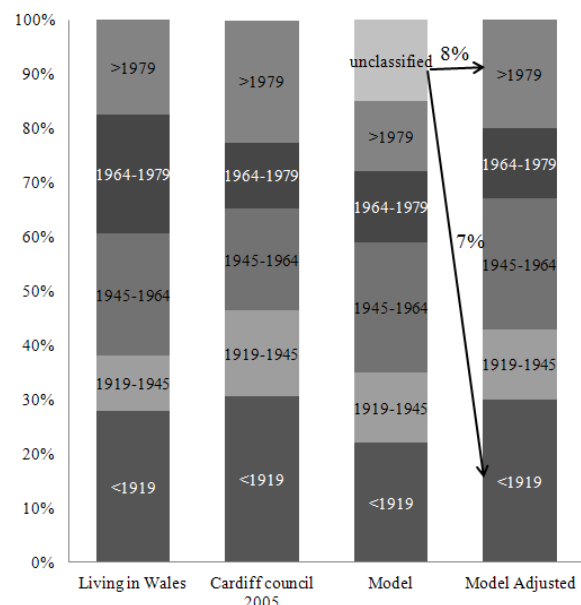


Figure 6: Age of dwellings comparison

Energy Demand of Dwellings

Monthly BREDEM based SAP tool

SAP is the UK energy compliance model that quantifies a dwelling's performance in terms of energy use per unit floor area based on the BRE's Domestic Energy Model (B R Anderson 1997). It takes into account the building's construction, location, heating systems and controls. The SAP sensitivity tool is based on a monthly version of BREDEM and estimates the energy consumption of space heating, water heating, lighting, electrical appliances and cooking. In BREDEM the total monthly energy use is calculated as outlined by EQUATION 1 (B R Anderson 1997).

$$Q(m) = Q_{prim}(m) + Q_{sec}(m) + Q_w(m) + E_{Lm}(m) + E_{Km}(m) \quad (1)$$

One of BREDEM's objectives is to compare different energy efficiency measures and "to carry out a detailed study of a particular house or household, using specific occupancy information" (B R Anderson 1997). The SAP sensitivity tool assumes a defined level of comfort and service provision to be delivered under a standardised occupancy condition which is based on a standardised occupant heating regime, temperature and heating pattern as well as the use of hot water, lights and appliances and the contribution made by metabolic gains (B R Anderson 1997).

Simple Model with Limited Parameters

According to (Firth 2010), the average house's CO₂ emissions based on the 2001 English housing survey is most sensitive to changes in occupancy, dwelling size, boiler efficiency, wall U-value and window U-value. It is also stated that the key factors affecting space heating are the dwelling's age and its built form i.e., the number of exposed walls, floors and roofs as well as the total floor area. It was decided to simplify the 15 typologies to 4, retaining only the core typologies: detached, semi detached, terraces or flats, thus removing any details on dimensions and retaining only information concerning the exposure of outer surfaces.

The tool used is a web calculator designed to provide approximate SAP ratings by concentrating on the most crucial and commonly altered parameters, mostly relating to fabric and systems. Limitations have been made in the variety of information that the user can process, with the intent of preserving simplicity of use (E. Crobu 2013). Both inputs and outputs are visible on a single screen with a maximum of 12 values to choose from for each of the 22 variables. Two outputs of the tool were used in this model which were: electricity used (kWh/year) and space and water heating usage (kWh/year).

The variables are split into 3 groups: Building overview, fabric and systems. These give the basic but essential options needed to distinguish physical properties that influence energy demand:

Building Overview	Fabric	Systems
Location	Thermal mass	Primary heating fuel and system age
Typology	Walls U-value	Secondary heating fuel type
Floor Area	Floor U-value	Infiltration rate
Orientation	Roof U-value	Ventilation
Surface ratio	Windows U-value	Solar thermal
Obstacles	Glazing ratio	PV panels
Lighting	Window shading and overhang	
	Thermal bridging	

Figure 4: Variables in SAP sensitivity tool by group

Variables by age, type and dimensions

It was decided to further group the variables in terms of their dependency on age, typology or independency from both, i.e. variables which are dependent on occupants, impossible to predict on a generalised level, or are constant for all dwellings in this case study. This is highlighted in figure 4, with those dependent on age in gray, on typology in black and those independent in white. Physical parameters identified as having the greatest affect on CO₂ emissions were given as much consideration as possible.

Age

Initially, age dependent values were determined by considering dwellings as they would have been built. The most influential parameters were then altered using statistical data on refurbishment levels to create progressive refurbishment steps for each age group with each one weighted according to its prevalence as can be seen in figure 5. Values used for walls, roofs and windows were based on statistical data from a report on private housing stock condition by Cardiff Council {FordhamResearch, 2005 #8}. No data relating to age of dwellings were available for heating system efficiency therefore values were based on data collected from EPCs for a nearby region.

Age 1

(Pre 1919)	15%	5%	10%	15%	35%	10%	5%	5%
Wall U-value	2.1	2.1	2.1	2.1	2.1	2.1	1.7	0.45
Roof U-value	2	0.6	0.6	0.6	0.6	0.35	0.35	0.35
Window U-value	4.8	4.8	3.1	3.1	3	2.2	2.2	2.2
Heating: Age	<06	<06	<06	>06	>06	>06	>06	>06

Age 2 (1919-1945)	10%	5%	15%	10%	40%	20%
Wall U-value	2.1	2.1	1.7	1.7	1.7	0.45
Roof U-value	2	2	0.6	0.6	0.6	0.35
Window U-value	4.8	3.1	3.1	3.1	3	2.2
Heating: Age	<'06	<'06	<'06	>'06	>'06	>'06

Age 3 (1945-1964)	5%	10%	10%	5%	40%	10%	20%
Wall U-value	2.1	1.7	1.7	1.7	1.7	0.45	0.45
Roof U-value	2	2	0.6	0.6	0.6	0.6	0.35
Window U-value	4.8	3.1	3.1	3	3	3	2.2
Heating: Age	<'06	<'06	<'06	<'06	>'06	>'06	>'06

Age 4 (1964-1979)	5%	10%	15%	45%	5%	20%
Wall U-value	1.7	1.7	1.7	1.7	0.45	0.45
Roof U-value	2	2	0.6	0.6	0.6	0.35
Window U-value	4.8	3.1	2.2	3	3	2.2
Heating: Age	<'06	<'06	<'06	>'06	>'06	>'06

Age 5 (post 1979)	10%	5%	15%	20%	30%	20%
Wall U-value	0.6	0.6	0.6	0.6	0.35	0.35
Roof U-value	2	2	0.6	0.6	0.6	0.35
Window U-value	4.8	3.1	3	3	3	2.2
Heating: Age	<'06	<'06	<'06	>'06	>'06	>'06

Figure 5: Weighted average levels of refurbishment for age groups

Type

The three variables identified: typology, surface ratio and obstacles could be simplified and derived for the 4 typologies. A 4th variable, total floor area that is closely related to typology and is known to have great impact on energy consumption has not been considered as being dependent on type but treated independently.

Dimensions

Detailed dimensions were straightforward to derive from GIS for each individual dwelling and were introduced into the model. Floor area was identified as one of the major factors affecting CO₂ emissions (Firth 2010). (V. Cheng 2011) also observes that the increase in total floor area with rising income (or socio-economic class) results in higher energy consumptions. It is also mentioned by (Firth 2010) that there is linearity between increase in floor area and CO₂ emissions.

Calculated dimensions for all dwellings were combined with the energy use results by varying the floor area in the SAP sensitivity tool for each version of each classification. A linear equation (one for electricity use and one for space and water heating) was derived to represent the energy use of the 20 classifications' weighted averages, dependent on the individual dwelling's dimension.

Aggregation and Validation

Aggregation

GIS was used to assign the relevant linear equations to each identified dwelling making use of the calculated floor areas. This meant that, although the model was confined to only 20 building classifications, in theory, there could have been as many different values for electricity and heating energy demand as there were dwellings. The electricity and heating use calculated for each dwelling were then aggregated per LSOA based on their spatial location.

Validation

Domestic gas and electricity consumption data were available at LSOA level from DECC (DECC 2010). They were formed by aggregating the actual readings of all meters within the areas. This set of data was used to validate the model, although there are a few issues to be noted:

- The data used is from 2010, therefore there could be very new developments included in the model which would not be accounted for in this data
- This data only considers gas and electricity usage. It is estimated that 6-7% of dwellings in the Cardiff area use other fuels as their main source of heating and therefore would also not be accounted for in this data
- Some LSOAs could have more or less domestic gas meter readings than there is in reality as all properties using below 73,200kWh/year of gas is automatically counted as a dwelling and could in reality be small commercial or industrial properties or vice versa

The 2011 census results for the number of households per LSOA were used to consider the differences in number of electricity meters, gas meters and dwellings identified in the model. The meter comparisons can be seen in figure 6 and was taken into account when analysing the final results.

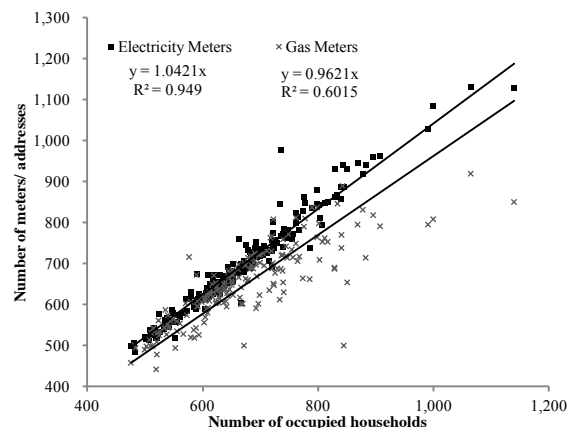


Figure 6: Number of households in 2011 Census against number of domestic gas and electricity meters in 2010 per LSOA

RESULTS

Domestic Electricity Consumption Results

The electricity consumption of dwellings aggregated per LSOA agreed with DECC's electricity meter readings on the same aggregated level. This can be seen in figure 7, which suggests that the method of combining the tool with the GIS data was successful.

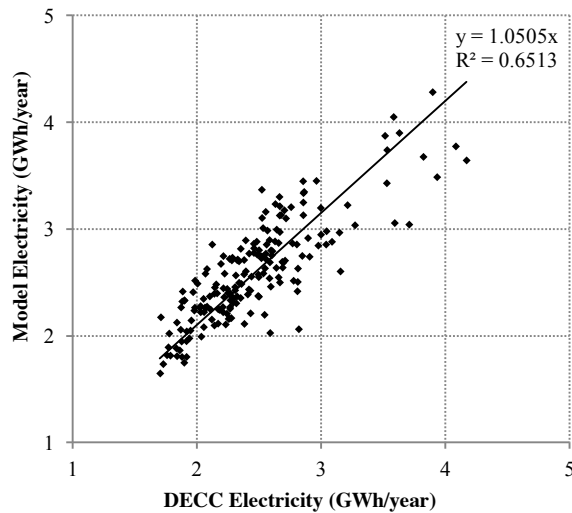


Figure 7: Model's Calculated Domestic Electricity Consumption compared to DECC electricity meter readings per LSOA

Initial Domestic Gas Consumption results

The initial results of dwellings' gas consumption compared with DECC's meter data, adjusted to account for off gas dwellings, was relatively precise but not as accurate as expected. The model seems to be overestimating energy demand for heating as can be seen in figure 8.

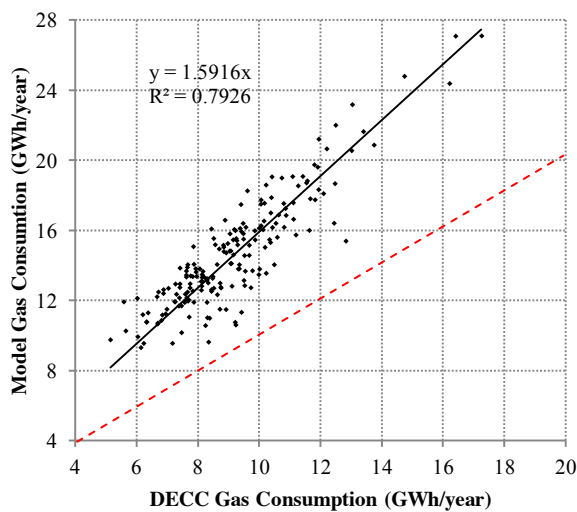


Figure 8: Initial Model's Calculated Domestic Gas Consumption compared to DECC's adjusted gas meter readings per LSOA

The model's performance in terms of electricity consumption implied that the method of inputting linear equations to represent weighted average levels of refurbishment for classified dwellings in GIS, in combination with data on dimensions, was reliable. In addition, it was shown that all sources were comparatively close when it came to the identification of dwellings (i.e. addresses and meters compared to the number of households per LSOA). This suggested that the overestimation of gas consumption was a consequence of the variables and assumptions used in the energy demand calculation and therefore were reviewed.

Four groups of variables and assumptions were considered questionable in terms of their accuracy and were identified as key factors affecting space heating:

- *Mean internal temperature* is highly dependent on occupants. SAP 2009 calculates the mean internal temperature for each month based on the heating requirement of a typical household while taking into account the physical properties of the dwelling. The mean is a combination of two values that are calculated; one for the temperature of the living area and another for the remainder of the heated space. The tool assumes that the living room is well heated at 21°C with the rest of the heated spaces at 18°C. (Wright 2008) suggests that in reality, these values could lie at around 20°C and 19°C respectively.
- *Heated floor area* could be slightly less than calculated in the model as the method assumes that all spaces within the perimeter of residential buildings are heated areas. This assumes that all spaces within the floor area are heated, when in reality, a portion could be unheated. It also does not account for the space taken up by the thickness of walls.
- *U-value of solid walls* could also be partly accountable for the overestimation. In situ measurements recorded in (C.Scott 2011) suggested that U values for traditional solid stone and brick walls are around 1.5W/m²K which is much lower than the SAP recommendation of 2.1W/m²K for pre 1919 dwellings.
- *Heating system efficiency* for gas central heating systems is defined by two values in the SAP sensitivity tool: Pre and post 2006. Estimation of their weightings in the model was based on data collected from EPCs for a nearby region. 20% of the sample of this region had G rated boilers with the rest rated above G. Translated to pre and post 2006, it was assumed that 30%

of dwellings had pre 2006 boilers (as is highlighted in figure 5) with 70% post 2006 boilers, i.e. A rated. The translation might underestimate the percentage that is A rated.

Refined Domestic Gas Consumption Results

Slight modifications were made to the 3 later variables above which brought the gas consumption predicted by the model closer to the aggregated meter readings. The model was then run under 5 different mean internal temperatures, from 17°C to 21°C as can be seen in figure 9. Considering the uncertainties associated with the measured meter readings, the refined results agree reasonably well. Figure 9 suggests that for dwellings in the Cardiff Local Authority, the average mean internal temperature is between 18°C and 19°C.

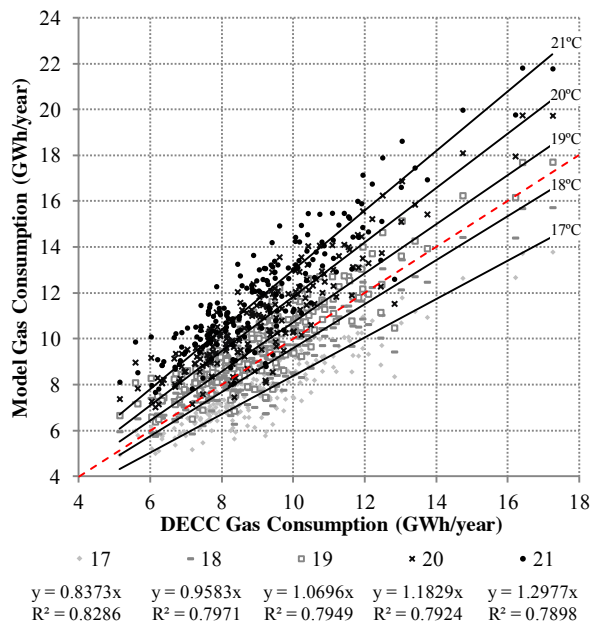


Figure 9: Refined model's calculated domestic gas consumption with 5 internal temperatures compared to DECC gas meter readings per LSOA

DISCUSSION AND CONCLUSION

It has been proved that the method of combining and refining the SAP sensitivity tool using GIS and data validation has the capability to model the energy consumption of a Local Authority in the UK. During its development, it was evident that accurate identification of dwellings was fundamental and that a similar level of care in validating the typologies and age would be needed if applied to other areas.

Initial refinement of the model proved successful and work will continue to improve the reliability further. The use of standard occupancy conditions has been identified by many as an inadequate estimation of real occupant behaviour due to a number of factors. Old dwellings are often heated to

a lesser degree due to the compromise between running costs and thermal comfort while heating energy use is under predicted for contemporary dwellings due to generally higher indoor temperatures (Cambridge Architectural Research 2009). Moreover, (V. Cheng 2011) states that households in deprived and affluent areas are likely to have different lifestyles and therefore differ in their energy consumption. (T. Oreszczyn 2005)'s study of actual measured indoor temperatures of 1604 low income households in England found that the median standardized daytime living room and bedroom temperature was 19.1 °C and 17.1 °C respectively with differentiations depending on property and household characteristics. Although initial refinement of occupancy conditions proved successful, disaggregating occupancy related inputs further could provide more meaningful results. I.e. readily available Output Area level data on households in terms of age, income or fuel poverty and physical properties of dwellings could be used to further adjust indoor temperature set points in the model. Research on occupancy patterns could also be used in a similar manner and more detailed, statistically based data on heating systems and fuel type could be introduced. The inclusion of other fuel types could prove vital if the model were to be applied to more rural areas with a higher proportion of dwellings off gas.

A similar method of validation and refinement will be carried out when applying the model as a prediction tool for energy efficiency and renewable energy technologies. This will investigate the capabilities of SAP based models in forecasting the impact of such energy saving efforts. (V. Cheng 2011) refers to past research that has found a consistent overestimation of the predicted savings in energy use and CO₂ emissions from retrofitting measures, known as the 'rebound' or 'take-back' effect. (S. H. Hong 2006) compared property and utility consumption data as well as room temperatures over a 2-4 week period over two winters from a total of 1372 properties. Between the two winters, loft insulation, wall insulation and new heating systems were installed in a sample. The differences in fuel consumption were compared with predicted improvements (based on a simple BREDEM model), but actual reduction was far less than anticipated. The evidence and reasons for discrepancies identified in such studies will be integrated into the next stage of the model.

It is hoped that with these advancements, the model could be effectively used and be a valuable prediction tool for energy efficiency and renewable energy technologies for Local Authorities and any area in the UK from neighbourhood to national level.

NOMENCLATURE

$Q(m)$	= Total monthly energy use (GJ)
$Q_{prim}(m)$	= Fuel used in primary heating system for each month (GJ)
$Q_{sec}(m)$	= Fuel used in secondary heating system for each month (GJ)
$Q_w(m)$	= Fuel requirement for water heating for each month (GJ)
$E_{Lm}(m)$	= Electricity consumption for lights and appliances for month m (GJ)
$E_{Km}(m)$	= Cooking fuel consumption for month m (GJ)

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