REGIONAL MODELLING OF DOMESTIC ENERGY CONSUMPTION USING STAKEHOLDER GENERATED VISIONS AS SCENARIOS

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ABSTRACT

UK Government Carbon emission reduction targets require large scale retrofitting of the built environment. Visions of a city region in 2050 have been developed through an in-depth participatory back-casting and foresight process. This paper will explore the modelling techniques required to simulate the necessary changes to achieve the retrofitting targets for dwellings. All of the visions achieve the 80% reductions required, using different pathways.

Building on earlier work based on "Bottom Up" urban scale modelling, this paper will describe the modelling of large areas using extensive data sources on the existing stock. Together with the scenario work, this research builds modelling of societal changes including population and household size, with domestic energy demand. The paper discusses the methods used and the sources of the data required to model these population and household changes.

The results generated from the model show the retrofit pathways from 1990, through present day emissions, to the required levels to achieve the targets set for 2050. In addition, the outcomes of the research are visualised through mapping of the pathways across a City region.

INTRODUCTION

The UK government has a binding target of 80% reduction in Carbon emissions by the year 2050, and it has been suggested that the vast majority of buildings that will exist in 2050 have already been built (Boardman, 2006). The process of retrofitting the existing domestic stock to reduce Carbon emissions through methods such as fabric improvements, occupant behaviour and renewable technologies has been researched in depth (Jones et al., 2013). When considering the building stock in 2050 it is important to have a scenario for the fuel mix that will be available. Work has been undertaken to create such pathways focusing mainly on the electricity grid. One particular work by UKERC created eight scenarios on a scale from "Business as Usual" to "Super Ambitious" (UKERC, 2013). However, the retrofit measures to be undertaken need to be cost effective and feasible (Carbon Trust, 2009), but not all buildings can be fully retrofitted at a reasonable cost.

Some modelling has been undertaken adopting a "Top down" approach, using a statistical model of the built environment based on demographic data from sources such as the census and other national datasets (Gouldson et al., 2012). This information is applied at lower levels of geography to give area-based resolution of the modelling. For example the DECC 2050 calculator (DECC, 2011). These models can only present the overall impacts of scenarios rather than a detailed view of the changes to the built environment.

The work presented here reflects the emerging regional priorities for south east Wales. The concept of a 'Cardiff city' region was a rather vague, without a clear geographic or administrative boundary, or governance structure. A broad view of the city-region was taken including the local authorities of Neath Port Talbot and Swansea to the west. This was intended to capture the strong economic connections between the three urban regions along the south coast (Newport, Cardiff and Swansea) which differ significantly from the neighbouring rural regions of West and Mid Wales.

The Cardiff City Region, as defined for the purposes of this paper, is home to some 1.86 million people. That is 60% of Wales' population despite spanning only 17% of its area. Indeed, the three urban centres of Swansea, Cardiff and Newport account for 24% of the Welsh population. Population density varies across the project area, with Cardiff by far the most concentrated.

The region has been divided by Welsh Government into four zones that cross the local authority boundaries, Head of the Valleys, Connections Corridor, Cardiff Coastal Zone, and Swansea Coastal Zone (Figure 1). These zones have been used in the visioning to express the population movement of the City region from 2014 to 2050.

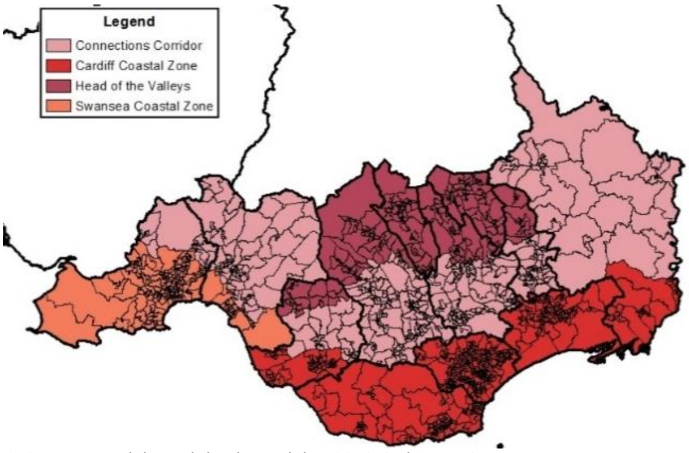

Figure 1 Regional zones (based on Welsh Government 2008)

Visioning process

The Retrofit 2050 project created three contrasting long-term (2050) visions for city-regional futures; these were developed through an extensive research process that spanned 2011-2013, and involved a series of workshops that brought together national experts in the fields of water, waste, energy and transport. These visions were intended as a tool that can be adapted and used by a wide variety of stakeholders and organisations to stimulate discussion and inform future policy and long-term planning (Eames et al., 2014).

The three visions each describe distinctive long-term visions of what a sustainable future might look like for core UK city regions in 2050. They comprise:

- A Smart-Networked City: the city as a hub within a highly mobile and competitive globally networked society.
- A Compact City: the city as a site of intensive and efficient urban living.
- A Self Reliant-Green City: the city as a self-reliant bioregion, living in harmony with nature.

Each of these futures is described by two key dimensions of change for systemic urban retrofitting: change in land-use and urban form, and social values and institutions.

Regional visions

The national visions were grounded in the Cardiff city region by the Retrofit 2050 project team using workshops incorporating regional stakeholders from local government, industry and civil society groups, semi-structured interviews with regional stakeholders and a desk-based review of relevant policy documents and grey literature.

The Cardiff 2050 City Regional Scenarios therefore represent an exploration of how these different articulations of urban sustainability can manifest and grounded in the economic, political, social, technological and ecological transformation processes shaping the development of Cardiff and South East Wales. The narrative for each of the Cardiff scenarios is built upon a 'pitch' developed by the participants during the regional workshop, intended to summarise Cardiff's bid for the prize of 'best retrofit city' in a fictional future 'European Sustainable Cities of 2050' competition. The very different assumptions about future population and settlement patterns embodied in the scenarios also reflect the divergent views of the expert participants in the regional workshop.

	Connected Cardiff	**Compact Cardiff - Wilderness Valleys**	**Orchard Cardiff**
Indicative population and population changes (2050)	2.75 million High population growth Inward migration	2.25 million Moderate population growth Internal re-distribution	1.75 million Moderate population decline Outward migration
Household size (2050) persons per house	1.95 Business as usual trend	2.32 City centre living	2.60 Return to 1970 household sizes
Change in building stock composition (2014- 2050)	640,000 New build 770,000 Retrofitted 30,000 Demolished	310,000 New build 660,000 Retrofitted 140,000 Demolished	60,000 New build 610,000 Retrofitted 190,000 Demolished

Table 1 Summary of scenarios (Eames et al., 2014)

The modelling of these visions explores the change in population and household size to develop a stock profile of the Cardiff City region in 2050 (Table 1). This profile has been modelled to guide policy makers to the extent of the retrofitting required to achieve the UK Government 2050 emission reduction targets.

Cardiff city Regions stock

A region's housing stock is a consequence of its past: of the techniques used when built and the major and minor modifications made through the years. Subtle and dramatic variations can be observed both between and within areas. Understanding and representing these variations is key to modelling the energy consumption of dwellings at a regional scale.

The Cardiff City Region defined in this research consists of 12 Welsh Local. Inland from these coastal urban areas is the South Wales coal field and the communities that evolved due to the industrial revolution. The region therefore consists of densely populated valleys and coastal cities as well sparser areas such as those found in the Vale of Glamorgan and Monmouthshire, which have remained largely rural in nature. When compared to the UK housing stock, Cardiff City Region's stock contains a substantially larger proportion of pre 1919 terraced houses with a relatively low proportion of new builds (Figure 2).

In order to model the region's future visions and allow the representation of potential economic and social situations, detailed analysis of the region's stock was required. The Office for National Statistics' hierarchical system builds up from clusters of adjacent postcodes into areas of a similar number of households (Output areas) forming a logical geographical base for analysing the housing stock. This modelling was carried out at LSOA level, which has good data availability, whilst also providing a relatively detailed representation of geographical variations within the regions housing stock.

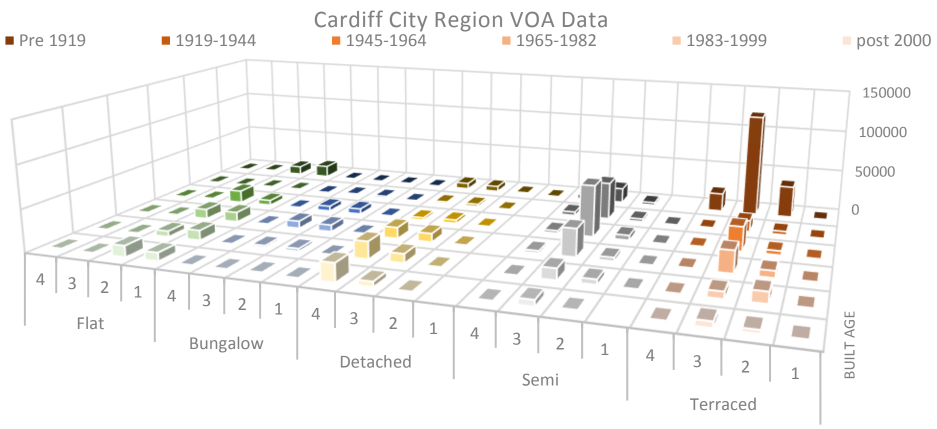

Figure 2 Cardiff City Region building stock breakdown (VOA data)

Modelling at an urban scale

Modelling the energy consumption of domestic buildings at an urban or regional scale has traditionally been undertaken in a top-down policy orientated way, where the gross energy consumption data provided by the energy suppliers is used as a starting point (Swan and Ugursal, 2009). This data is then analysed using stock surveys to give single composite buildings that can be analysed (Gouldson et al., 2012) using building modelling techniques. This top-down approach is reliant on historical data to produce predictions, rather than based on building physics modelling. The 'top down' approach has inherent difficultly in dealing with new technologies and changes in occupant behaviour and their likely impact on future energy consumption.

Alternatively, bottom-up approaches have the potential to model buildings in detail and account complex interactions of building occupants, passive design and active systems. Initial bottom-up the urban scale modelling approaches such as the Energy and Environment Prediction model (EEP) (Jones, et al., 2007) are based on steady state models, such as the Standard Assessment Procedure (SAP) (BRE 1998). Such models predict the energy consumption for archetypes of buildings representing the considered building stock. In a recent review (Sanaieian et al., 2014), EEP was still considered one of the primary methods for modelling energy performance of buildings at an urban scale. Kavgic et al., (2010) described the model as an exemplar and based their work firmly on its achievements.

Similar work has been carried out using the English House condition Survey as the base data, (Firth & Lomas, 2009 and He et al., 2015). However, using such models did not allow for achievement of the 80% targets. This highlights the need for bottom up modelling to consider the additional impact of renewable technologies, the decarbonising of the grid and the change in the building stock profile.

EEP model

The EEP model simplifies the simulation of the urban environment by using simple standard energy prediction tools, and ways of grouping houses together. The grouping of houses usually follows the type of house e.g. terraced, semi-detached or detached. To improve this grouping, the house size and age are considered. A number of common house types are surveyed, and the results of these surveys are clustered together to give groups of houses with similar energy predictions.

The EEP model uses the UK government's SAP as the method for measuring the Carbon emissions related to residential building stock. The model within EEP has been adapted to allow the modelling of fabric retrofit, building integrated renewable technologies and occupant behaviour. The EEP model allows for "what if" functions to target different retrofit options, and this capability has been developed further using the pathways to 2050 low Carbon residential building stock (Lannon et al., 2013). The impacts of housing retrofit, renewable technologies, occupant behaviour, and grid decarbonisation were modelled at a local authority scale. The results were then visualised using a client web application, or 'demonstrator,' which was developed to allow stakeholders to engage with the modelling process.

When considering the city region in the EEP model population and household size predictions are required to estimate the stock requirements. Population projections from the Office of National Statics (ONS, 2011) were combined with the stakeholder derived visions for 2050 allowing the domestic energy demand for a small census area to be tracked through time.

Data sources

As large numbers of dwellings are considered when studying a city or region, to save effort, it is important that the information about each dwelling is easy to collect and model. A number of potential datasets were investigated to assess them in terms of ease of use and suitability, including Valuation Office Agency data that has a complete breakdown of property types down to LSOA level, and the UK Map dataset that is a GIS based classification of building blocks – age, typology, floor area and building heights. These building based datasets were used with the Census that has a wide range of single or bivariate data on LSOA or OA level. Finally, energy efficiency measure installation data is required to predict the energy performance of buildings. The Energy Saving Trust's Home Energy Efficiency Database (HEED) (EST 2010) which contains records of energy efficiency installations grouped by local authority, age and typology and DECC's NEED (DECC 2013a) database which is a weighted sample of properties on a regional level were used.

From these datasets a procedure was developed for use within the model that groups together dwellings with similar energy performance characteristics creating 'house types'. The characteristics chosen for the grouping are considered to have the greatest influence on domestic energy performance (Table 2).

Built Age	Pre 1900, 1900-1918, 1919- 1929, 1930-1939, 1945-1954, 1955-1964, 1965-1972, 1983-1992, 1993-1999, 2000-2009, 2010-2014, Post 2014
Dwelling typology	Bungalow, Detached, Flat/maisonette, Terraced, Semi-detached
Bedrooms	1, 2, 3, 4+,

Table 2 Property Types – Age, Typology and Size

City region scenario modelling

The starting point for modelling the developed scenarios was to create a baseline model (2014/15) of the city regions housing stock in its current state. The baseline model used the Valuation Office Agency's (VOA) 2014 database of the UK's current housing stock per LSOA. The data gave the number of each property type in each LSOA including one of 12 built age periods, one of 5 typologies and count of bedrooms (1, 2, 3 and 4+). These 240 archetypes split further to geographically represent fuel usage based on census 2011 statistics on central heating types per LSOA. The resulting archetypes were modelled in SAP2012 based on how they would have originally been built but with the approximated current heating systems.

The HEED database was then used as the main source of information for modelling improvements made to these archetypes to current date (these changes represent post 1990 improvements as no pre 1990 HEED data exists). Although HEED records cover a wide range of fabric improvement measures, the model grouped improvements 4 fabric improvement groups: loft insulation, cavity wall insulation, solid wall insulation and double glazing. A proportion of each archetype for each LSOA was then modified to represent the level of retrofit carried out since 1990.

In order to approximate the number of dwellings that received fabric improvement measures prior to 1990, data from the 2013 UK housing fact file (DECC 2013b) was used for the years 2011 and 1990. The percentage of homes that had received fabric improvements was compared to the amount of records in the HEED database. From this, it was deduced that the amount of walls insulated prior to 1990 was negligible. The amount of double-glazing installed prior to 1990 and the amount of loft insulation installed prior to 1990 could be approximated as 60% the amount currently recorded. Additional sets of modified clusters were created to represent pre 1990 retrofit of glazing and roofs.

The final step of representing current retrofit levels in the model was to represent the occurrence of multiple measures applied to an archetype. NEED data was used to approximate the distribution of multiple measures for groups of properties. The groups were based on NEED's distribution of properties (5 age groups and 4 typologies). The count of measures attributed to each of these groups in the model was correlated with the occurrence of single and multiple measures in the NEED database to derive the approximate distribution of measures in the model.

From the baseline of 2014/15, the stock model was traced back to 1990 with the purpose of measuring the visions' ability to reach the 80% reduction in Carbon emissions by 2050 compared to 1990. This was done by eliminating properties built after 1990 (determined by VOA post 1993 age groups) and any improvements made thereafter as well as representing changes in type of fuels used, emission factors, household sizes and occupant behaviour. For the city region's stock, pathways to 80% reduction could then be modelled according to the three visions in steps of five years from 2015 to 2050.

The 2050 scenarios developed for the region outlines the approximate number of dwellings built and demolished by the year 2050. Within the narratives of these visions, conditions for the demolition and building of new dwellings were derived. The Connected Cardiff scenario shows a large number of new buildings in the peri-urban and less dense urban areas. This is seen as an expanding housing supply with 640,000 new dwellings throughout the region. The Compact Cardiff - Wilderness Valleys scenario expresses a moderate increase of new build in less dense urban areas, a growth of medium to high density urban conurbations, and high density neighbourhood centres within/around Swansea, Bridgend, Cardiff and Newport. This growth is offset by a significant number of the valleys towns being uninhabited, uplands demolished, and more wild sparse hinterland. The demolition rate is around 17%. The final scenario, Orchard Cardiff, shows the demolition of poor dense stock and urban/peri-urban stock with a demolition rate of 24%.

These conditions can be modelled on LSOA levels using the four geographical indicators rurality (Figure 3), flood risk (figure 4), regional zone (Figure 1) and density as a percentage of built upon land. Some of the vision data such as the consideration of a green belt cannot be modelled as identification of geographical areas within the LSOA would be required. As the model is based on LSOA level data, these conditions are not modelled for the demolition and new build in the compact vision. In spite of this, it is hoped that the modelled scenarios using the above indicators can represent the three visions of urban sustainability reasonably accurately.

For each of the three visions, a set of criteria was developed for an individual LSOA to establish the amount of new build and demolitions. These criteria consider the available land, the required number of properties and the overall scenario for migration. For example for the new building count in the Compact City, region flood risk reduces the available land area but new build will only occur in the coastal and corridor regional zones. For the demolition count, the migration from the Heads of the Valleys will increase the demolition rate in the peri-urban and urban areas to the north, but the rural areas will remain static.

RESULTS FROM MODELLING

The outcome of the modelling process allows the Cardiff city region to be modelled from 1990 to 2050. The population and household size projections for the three visions are very different and the modelling of these considering the data at a LSOA level shows the different pathways to the visions in 2050.

In the maps of number of households (Figures 5 to 8) the existing levels show a reasonable consistent level of building density throughout the region (Figure 5). The Connected Cardiff vision takes advantage of the lower valleys' connected corridor as a resource for increasing housing, building on the proposed Metro and a shift towards the use of public transport to deliver future development of the economy. This is shown with an increased urbanisation of the corridor highlighted by the dark red LSOAs on the map (Figure 6).

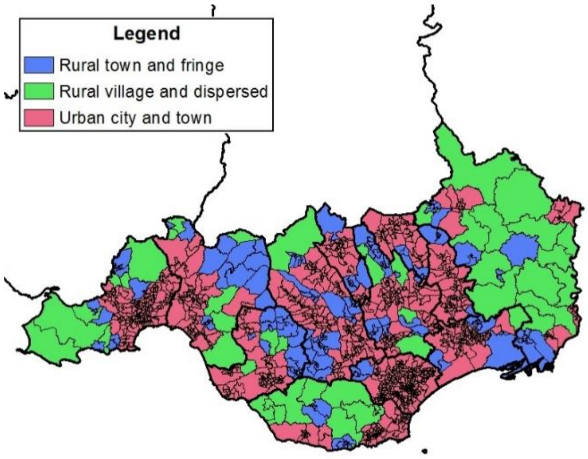

Figure 3 LSOA rurality (ONS 2011)

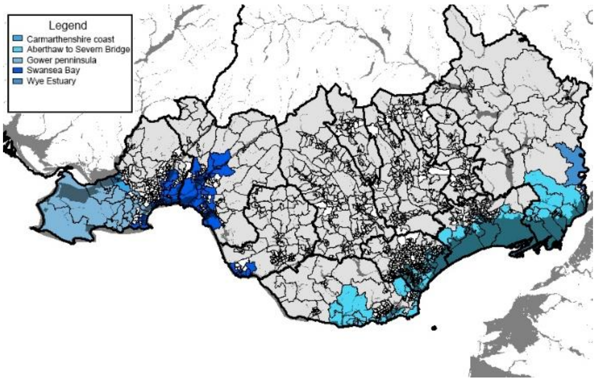

Figure 4 Flood risk map for City region (EA 2014)

The Compact Cardiff vision deals with flood risks through flood defences based upon tidal lagoons and barrages and shows massive densification of housing (darker southern LSOAs) in the coastal zone of the city region. In addition the re-wilderness of the upper valleys lead by the demolition of hard to treat housing is shown by the lighter shades towards the north and the Heads of the Valleys zone (Figure 7).

The Orchard Cardiff vision expresses the greening of the city centres (lighter shades) and the increase use of the new Metro system to provide access to land throughout the city region (Figure 8).

The number of households for each scenario can be further explored to establish the predicted stock mix. A type of dwelling of particular interest is the “hard to treat” solid wall dwellings. The results have been compiled at a Local Authority level (Table 3) and these show a large reduction for the Heads of the Valleys areas (Blaenau Gwent and Merthyr Tydfil) with roughly 2% remaining in the Compact Cardiff scenario. In contrast, the Costal Zones (Cardiff, Newport and Vale of Glamorgan) are reduced to 10% to 34% in the Orchard Cardiff vision.

	Solid wall properties in 2014	Remaining Connected Solid wall Dwellings	Remaining Compact Solid Wall Dwellings	Remaining Orchard Solid Wall Dwellings
Blaenau Gwent	14,700	98%	2%	84%
Bridgend	15,602	95%	50%	76%
Caerphilly	25,389	96%	66%	81%
Cardiff	37,380	96%	86%	10%
Merthyr Tydfil	11,520	96%	2%	77%
Monmouthshire	8,450	48%	97%	78%
Neath Port Talbot	19,860	86%	93%	64%
Newport	14,970	95%	60%	25%
Rhondda Cynon Taf	53,070	98%	65%	87%
Swansea	29,480	90%	100%	41%
Vale of Glamorgan	12,550	89%	98%	34%
Torfaen	7,720	94%	53%	69%
Grand Total	250,691	93%	69%	59%

Table 3 Solid wall construction dwellings for each Local Authority

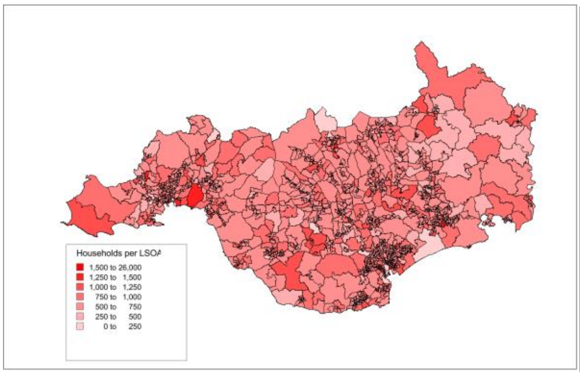

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Figure 5 Existing households per LSOA

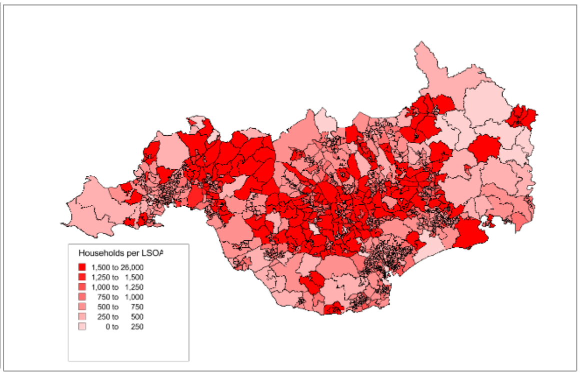

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Figure 6 Households per LSOA for Connected Cardiff Vision

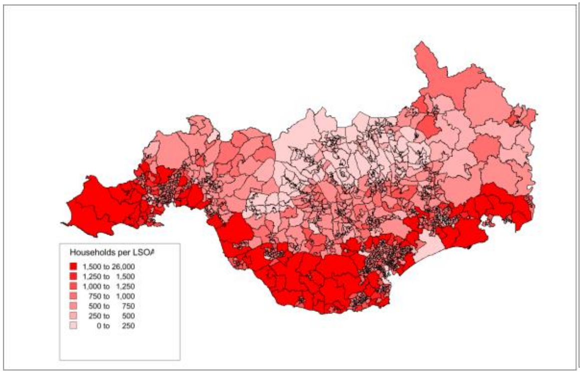

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Figure 7 Households per LSOA Compact Cardiff Vision

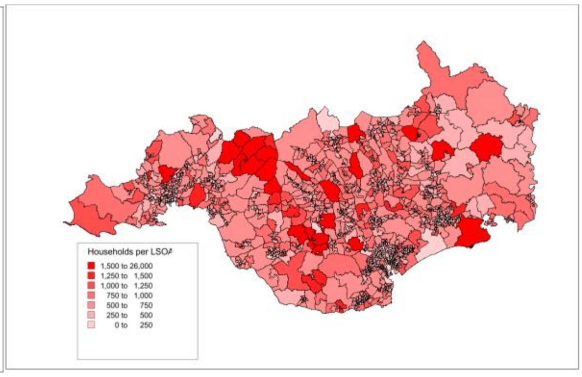

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Figure 8 Households per LSOA Orchard Cardiff Vision

In the three visions the mix of building stock varies considerably, and this is shown in the reduction in heating demand for the stock (Table 4) with the Orchard Cardiff vision showing a 29% reduction assuming no retrofit has been undertaken.

	Space heating demand TWh	Reduction over 2014
2014	13.9	
Connected Cardiff	12.9	7%
Compact Cardiff	11.5	17%
Orchard Cardiff	9.9	29%

Table 4 Heating Demand for each of the visions assuming no retrofit measure applied after 2014

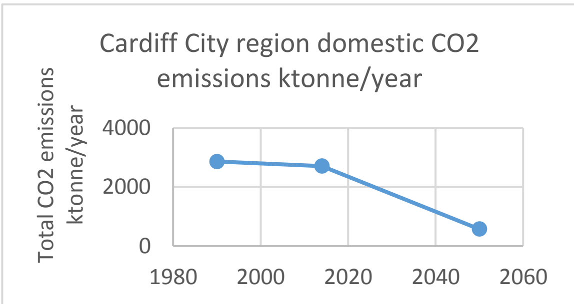

Figure 9 Overall progress to the 80% target reduction in Carbon emissions

When the region is considered as a whole, the vision process is based on the premise that Carbon emissions will be reduced by 80%. Using the modelling that has been undertaken it can be seen that there has been a 5.5% reduction in emissions in the 24 years from 1990 to 2014 (Figure 9). This leaves the remaining 74.5% reduction to take place over the next 36 years. To show the scale of the task in hand, in terms of annual reduction, from 1990 to 2014 there has been a 0.2% annual reduction, however every year until 2050 will need an annual reduction of 2%.

CONCLUSION

The paper has shown that it is possible to build a "Bottom Up" urban scale model to describe the domestic energy demand of large areas using extensive data sources of the existing stock. This model has been merged with a scenario work based on City Regional visions of a future that achieves the 80%

target. The model includes societal changes represented by population and household size together with geographical indicators such as rurality, flood risk, regional zone and density as a percentage of built upon land. The sources of the data required are becoming more available and complete and as such can provide more confidence in model outcomes. The methods of modelling population and household changes are generally applied at a Local Authority level, and in this model they are combined with housing data (VOA data) and migration and stock levels gained from the visions.

The results generated from the model show the retrofit pathways required to achieve the targets set. The outcomes of the research have been visualised through mapping of the household numbers for the Cardiff City region.

ACKNOWLEDGMENT

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REFERENCES

Boardman, B. (2006). The challenge of existing UK houses, Paper presented at the IABSE Henderson Colloquium, Cambridge, UK.

BRE, 1998. The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Building Research Establishment for DETR, Garston.

Carbon Trust, 2009, Building the future, today, CTC765, Carbon Trust, London

DECC 2011, DECC 2050 Pathways calculator, Available at: http://2050-calculator-tool.decc.gov.uk

DECC 2013a, National Energy Efficiency Data-Framework (NEED)

DECC 2013b, United Kingdom housing energy fact file.

Eames, M., De Laurentis, C., Hunt, M., Lannon, S. and Dixon, T. 2014. Cardiff 2050: City regional scenarios for urban sustainability. Working paper. Cardiff University.

Environment Agency 2014, Flood maps,

Energy Saving Trust 2010, HEED Online 2,Full Technical Guide 2.0.

Firth, S., and Lomas, K. 2009, Investigating CO2 emission reductions in existing urban housing using a community domestic energy model, International Conference of the IBPSA.

Gouldson, A., Kerr, N., Topi, C., Dawkins, E., Kuylenstierna, J., Pearce, R. 2012, The Economics of Low Carbon Cities. A Mini-Stern Review for the Leeds City Region. University of Leeds.

He, M., Brownlee, A., Lee, T., Wright, J., Taylor, S. 2015, Multi-objective optimization for a large scale retrofit program for the housing stock in the North East of England

Jones, P. J., Lannon, S. C. and Patterson, J. L. 2013. Retrofitting existing housing: how far, how much? Building Research and Information 41(5), pp. 532-550. (10.1080/09613218.2013.807064)

Jones, P. J., Patterson, J. L. and Lannon, S. C. 2007. Modelling the built environment at an urban scale - Energy and health impacts in relation to housing. Landscape and Urban Planning 83(1), pp. 39-49. (10.1016/j.landurbplan.2007.05.015)

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, D., Stevanovic, Z., Djurovic-Petrovic M., 2010. A review of bottom-up building stock models for energy consumption in the residential sector, Building and Environment 45 (2010) 1683–1697

Lannon, S. C., Georgakaki, A. and Macdonald, S. 2013. Modelling urban scale retrofit, pathways to 2050 low carbon residential building stock. Presented at: 13th International Conference of the IBPSA, Chambery, France, 25 - 28 August 2013.

Office for National Statistics, 2011. Census: Aggregate data (England and Wales). UK Data Service Census Support.

Sanaieian, H., Tenpierik, M., van den Linden, K., Mehdizadeh Seraj, F., Majid Mofidi Shemrania, M., 2014. Review of the impact of urban block form on thermal performance, solar access and ventilation, Renewable and Sustainable Energy Reviews 38 (2014) 551–560.

Swan, L.G., Ugursal, V.I. 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques, Renewable and Sustainable Energy Reviews, 13(8): 1819-1835.

UKERC. 2013. The UK energy system in 2050: Comparing Low-Carbon, Resilient Scenarios

Welsh Government 2008. People, Places, Futures The Wales Spatial Plan 2008 Update.