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Understanding the complexities of domestic energy reductions in cities: Integrating data sets generally available in the United Kingdom's local authorities

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ABSTRACT

This paper describes the development of a spatial database for an annual energy consumption framework. As the database of the existing building stock is a weak point in most European cities but possible pathways to energy reduction in the building sector have to be found, this paper is of high relevance. Our framework uses a complex multi-source data set and a plethora of statistical methods to merge various large complex data sets and then apply a heat balance model in three sub-city areas in Newcastle upon Tyne, United Kingdom. The framework estimates the energy end-use at the single dwelling level on three aggregated scales: district, neighbourhood and communities. We propose a methodology for modelling energy in buildings in different ways depending on the required output scale, the cluster top-down model and the domestic energy model (DEM) bottom-up approaches. The cluster model is a generalization of similar building energy profiles into archetype medoid prototypes in districts and eventually the whole city, whereas the sub-city DEM is a representation of an individual building energy pro- file in neighbourhoods and communities. The framework can be used to test different energy measures (fabric and heating supply systems) for the same property type, and give insights into community energy analysis by aggregating individual building energy consumption. These insights will enable rational and considered responses to be formulated to the problems of integrating renewables into the generation portfolio, that are likely to be faced in the future.

1. Introduction

After a series of European policy initiatives (e.g. the European Strategic Energy Technology Plan and the Partnership for Energy Efficiency Cooperation), European cities are now in need to ensure that new buildings, as well as large existing buildings meet certain minimum energy requirements. It also requires that all buildings should undergo ‘energy certification’ prior to sale, and that boilers and air conditioning equipment should be regularly inspected. However, a unique future national energy scenario would translate into many alternative energy futures pathways at the local authority (LA) scale. As a result, LAs require a spatial understanding of end-use energy demands in targeted city areas to provide evidence for meeting future challenges in planning local energy services and infrastructure. The geographical coverage is closely associated with the purpose, i.e. a descriptive energy model could draw a baseline for the city energy consumption. In this energy modelling research approach, the concept of spatial data integration ensures multi-sourced data and interoperability. The information can be integrated through key identifiers and the result is a comprehensive, spatially enabled database in the energy model. A robust spatial and modelling methodology would enhance the effectiveness of their local energy planning of future interventions of energy efficiency measures, decentralized energy supply infrastructure. For instance, in each city of the United Kingdom (UK) some local areas might be more suited for building envelope technological interventions such as those promoted by the Green Deal whereas others may benefit from centralised and distributed energy supply options.

The literature on energy system frameworks involves different (sometimes linked) approaches for the purpose of decision analysis. Examples are: Ascione et al. (2013) use a combined method of already

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available information and energy audits on a sample of buildings to quantitatively estimate the energy consumption for each building. Trigaux, Oosterbosch, De Troyer, and Allacker (2017) use a design tool that extracts solar obstruction data, building geometry and constructing elements, and then uses this information to assess the heating energy demand based on the dynamic Equivalent Heating Degree Day (dEHDD) method. Ma and Cheng (2016) use a Big Data methodology (Hsu, 2015) for integrating a large number of predictors and a Geospatial Regression method for filling the blanks in the data set. The Ma and Cheng method then rank the features and estimate the energy use in a single building using a case study in New York City. Vartholomaios (2017) uses a standardized rank regression coefficient sensitivity technique on a parametric study of three urban topologies to understand the co-influence of the urban form parameters on the energy consumption. Yeo, Yoon, and Yee (2013) use an Energy Integrated Planning Support System to model urban space, which predicts urban micro-climate and energy demands. The Yeo et al. model includes a function to ultimately visualize the 2D and 3D information for energy planning in the city. In the United Kingdom, Rylatt, Gadsden, and Lomas (2003) propose an innovative use of Geographical Information System for Estimating Municipal Energy for Residences using Arbitrary Levels of Data (EMERALD) based in the Building Research Establishment Domestic Energy Model (BREDEM) (Anderson & Chapman, 2010) that produce monthly predictions of annual energy use for space and water heating, lights, cooling and appliances.

Our paper argues that energy planning at decentralized level would be to prepare an area-based DTS to meet energy needs using a bottom-up approach and disaggregated data (Hiremath, Shikha, & Ravindranath, 2007, p. 735). This paper presents a framework to estimate spatial domestic energy consumption in individual dwellings and aggregated areas using a spatially enabled database to represent local area characteristics. We use a cluster framework for districts and a sub-city DEM framework for neighbourhoods and communities, the Newcastle CarbonRoute Framework (NCRF) database. NCRF is a spatially referenced parameterised per-dwelling domestic energy framework developed with the purpose of estimating the energy consumption of sub-city areas. Two types of modelling were carried out. In the first, top-down, using K-means clustering of dwelling archetypes and the second a sub-city Domestic Energy Model (DEM) that creates individual energy consumption estimates for each dwelling and aggregates these to sub-city areas.

Principal component analysis underpinning the cluster model was used to provide both a method for explaining how many of the surveyed categorical variables are needed to explain the total variance within the reduced data set, and to detect the correlations between the variables. Besides these more obvious uses, this study has shown that there is an additional benefit as the principal component also provides group estimates of English Housing Survey 'donor' records before the Newcastle CarbonRoute Map (Calderón, James, Alderson, McLoughlin, & Wagner, 2012) nearest neighbour multiple imputations method actually selects the best 'donor' in an augmentation strategy for inputting to a BREDEM type model. This shows that the principal component analysis is a worthwhile process; however, it remains to be seen whether the principal component results will be transferable to other cities because regional climates make for different insulation and heating supply requirements. However, as this paper has demonstrated the NCRM data sets are generally available in some form to many, if not all, local authorities and other local authorities should consider this type of approach to collate data from existing sources with the requirement that there has to be a large sample so its application will be statistically valid.

The NCRF is likely to be of significant value as a policy tool. It can be used to inform and direct policy by testing the effect that various policy decisions are likely to have on the community energy consumption. For instance, the framework could be used to test the effect of possible future revisions to the Building Regulations or energy

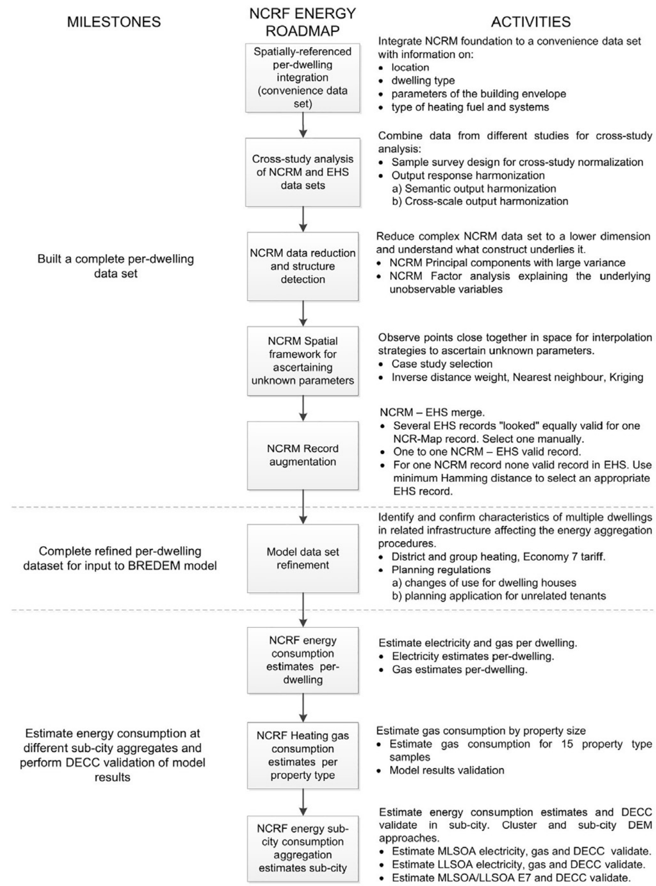

Fig. 1. NCRF energy estimates roadmap.

efficiency schemes. We believed that current UK Government regional and sub-city methods and data for domestic properties in its current most disaggregated form may not accurately represent energy consumption of geographically specific and homogenous urban areas in the UK and therefore be insufficient for providing evidence for meeting future challenges in planning local energy services and infrastructure; also, NCRF will significantly increase our theoretical understanding of the complex interrelationships that exist, not only between the various end-uses of energy within the demand side of the UK housing stock, but also the relationships that exist between the demand side and a particular combination of urban form, climate, buildings physical characteristics and behaviour and household social practice (Shove & Walker, 2014) in a sub-city area.

From Fig. 1, this paper is organized as follows: Section 2 is a brief review of the initial data sets. Section 3 explains the procedures to integrate the local and the national data sets to produce an augmented Newcastle CarbonRoute Framework (NCRF). Section 4 explains the NCRF model refinement. Section 5 uses the Cambridge House Model (CHM) to estimate annual electricity and gas consumption and finally Section 6 makes the discussion and the conclusions and the concluding remarks are in Section 7.

The software components used in NCRF are in two different contexts and two kinds: (i) using components that are parts of a commercial executable e.g. the spatial interpolation components from the ArcMap™ from ESRI or CHM, or (ii) using executable modules custom made for this study, and called Structured Query Language (SQL) scripts. As a summary, Fig. 2 is the main computing process flow leading to the NCRF energy consumption estimates.

The diverse nature of the inputs into the NCRF has resulted in a significant library of PL/SQL scripts used for cleaning, sorting, importing and linking NCRM data. The modular nature of the