Modelling household spatial energy intensity consumption patters for building envelopes, heating systems and temperature controls in cities.

Javier Urquizo[a,c,*], Carlos Calderón[a], Philip James[b]

[a] *School of Architecture Planning & Landscape, Newcastle University Newcastle upon Tyne, UK, NE1 7RU*
[b] *School of Civil Engineering & Geosciences, Newcastle University Newcastle upon Tyne, UK, NE1 7RU*
[c] *Escuela Superior Politécnica del Litoral, ESPOL, FIEC, Campus Gustavo Galindo Km. 30.5 Vía Perimetral, P.O. Box 09-01-5863, Guayaquil, Ecuador*

Abstract

This paper explore the benefits of a bottom-up spatially enabled engineering building-based energy framework in identifying neighbourhoods, and community's building aggregated areas with spatial patters. We argue that an area-based approach allows more houses to be targeted in places where local area characteristics show inefficient elements, and may therefore potentially capture a greater number of households per unit of cost, compared to the existing self-referral methods. We propose a spatial method to show the extent of building envelopes, heating systems and temperature controls. Heating controls, which are not recorded in the United Kingdom Homes Energy Efficiency Database (HEED), but we believe would be considered good practice to maintain balanced temperatures around the house, and also potentially reduce the complexity in modelling the thermal zones. Additionally, heating controls are seen as compulsory in new building regulations, an eligible measure in Green Deal and Energy Company Obligations, and in the United Kingdom Department of Energy and Climate Change (DECC) heat strategy. This paper has taught us that the emerging picture surrounding local energy modelling and that, for example, singularities such as group heating and district heating (decen-

* Corresponding author
Email addresses: jurquizo@espol.edu.ec (Javier Urquizo), carlos.calderon@newcastle.ac.uk (Carlos Calderón), philip.james@newcastle.ac.uk (Philip James)

tralised energy supply) have a great impact on final energy consumption calculations.

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1. Introduction

The first reason for researching energy use in cities is that it is rapidly increasing. Cities use a significant proportion of the world's energy and because urban population and economic activities within the city are also increasing, the urban energy use is also projected to grow. The Organisation for Economic Co-operation and Development [1, pp. 137] argues that by 2008 half of the world's population lived in cities, and by 2030 cities will house 60% of the worlds population, equivalent to the total global population in 1987. Detailed analysis from the International Energy Agency [2, pp. 44] shows that global energy use in the residential sector increased 19% between 1990 and 2005. The second reason is that the Local Authorities (LAs) [3] play a key role in the achievement of the energy and climate objectives through formal commitment to be achieved by the implementation of Sustainable Energy Action Plans. This stems from their direct energy use in the building stock, but also because they act as planners, and have the authority to regulate various activities (e.g., community energy services). Cities are also producers and suppliers of energy (e.g., district heating schemes), and most importantly have experience in translating international and national policies (e.g., [4] on the energy performance of buildings) into local actions.

In the last five years, there has been interesting domestic energy research in cities using the spatial approach. This review will provide a useful understanding of current efforts made by energy modellers to provide a solution for the urban energy consumption patterns planning. Examples include: [5], who addressed the scale of the modelling by proposing a 'whole building' self-contained unit (SCU) as a physically meaningful unit that has its own energy metering and its relationship to buildings. This approach allows city-scale modelling based on the characteristics of an individual building in Leicester. [6] used a three-dimensional digital model of the city of London to make a series of geometrical measures: building volume, exposed surface area and plan depth. [6] found a strong correlation between the exposed surface area with the combined energy consumption, and the plan depth and the electricity consumption.

From the literature review, it is clear that spatial modelling is an important aspect of energy consumption; also local energy consumption patterns are important to alleviate fuel poverty [7] and for micro-generation supply [8]. This paper attempts to address some of these issues - or shortcomings for other models - and also the important impact on policies [9] in sub-city areas. Our work is one of the first modelling exercises to be undertaken within the city limits that are set in the context of a unique identification of Local Land and Property Gazetteer in a spatially enabled database to explore similar patterns of energy consumption and identify building aggregated areas with spatial expression patterns most similar to a given parameter within the building energy profile. The National Land and Property Gazetteer is updated on a continual basis by the local authorities in England.

Furthermore, the literature review has highlighted the benefits arising from a spatially enabled approach. From the spatial analysis, our paper show that it is possible to use operators and develop queries that enable: the representation of key energy estimators, a comparison of the effect of using different local area characteristics on the patterns extracted, which are potentially useful for measures below local authorities in sub-city areas. Our paper links secondary sources either by Unique Property Reference Number (UPRN) code, Topographic Identification (TOID) and/or address, instead of using a grossing methodology that adjusts national dwellings to totals by region. The secondary information is generally available in some form to many, if not all, local authorities

Using a case study from the United Kingdom [10], we develop a bottom-up spatial local energy end-use framework [11] that sets out the sub-city energy aggregated planning direction, the Newcastle CarbonRoute Framework (NCRF), and establishes the single dwelling as our unit of detail. NCRF is a spatially referenced parameterised per-dwelling domestic energy framework developed with the purpose of estimating the energy (electricity and gas) consumption of sub-city areas. Elsewhere, [12] analysed holistically the residential energy consumption patterns and the overall housing energy requirements of urban and rural households in Finland. In the United States, [13] analysed patterns of direct fuel consumption for on-road transportation and in buildings and industry in urban counties.

The aim of this paper is to use the NCRF spatially enabled model and rich thematic database facilities in developing queries that enable spatial analysis, i.e., a comparison of the effect of using different local area characteristics on the patterns extracted, which we argue are potentially useful to inform the design of energy efficiency policies in sub-city areas.

This paper is structured as follows: Section 2 explains the data formation and assumption of the NCRF. Section 3 reviews the key Energy Efficiency directive (EED) and the Energy Performance. Section 4 analyses the spatial characteristics of the energy consumption patterns of building envelopes, heating systems and temperature controls. Section 5 discusses these findings, and finally, Section 6 makes suggestions concerning the relevance of these findings.

2. Domestic energy model framework

This section describes the assumptions within the developed of NCRF and how these affect the analysis of the results. Figure 1 shows the NCRF energy intensity estimation. As can be seen in Figure 1, the NCRF framework is comprised of the Newcastle Carbon Route Map (NCRM) data sets [14], energy modelling aggregation, validation method and energy spatial patterning.

Four classes of data sets were used to build NCRM: dwelling domestic stock data, building physics data, household data and climate data, and each one is described in turn here. The assumptions in the modelling methods are described in Sections 2.1 to 2.3 and DECC and NEED data is used to assess the performance of the framework is in Section 2.4.

The NCRM has two data sets at the resolution of the individual dwelling, with one

NOMENCLATURE

AECI the Annual Energy Consumption (use) Intensity (density)

BREDEM The Building Research Establishment Domestic Energy Model

CHM Cambridge Housing Model

CHP Cogeneration of electricity and heat

DA Data aggregators

DECC United Kingdom Department of Energy and Climate Change

DFEE the Dwelling Fabric Energy Efficiency Methodology

DUKES Digest of UK energy statistics

EED Energy Efficiency Directive

EHS English Housing Survey

HEED United Kingdom Homes Energy Efficiency Database

LAs Local Authorities

LLSOAs Lower Layer Super Output Areas

MLSOAs Middle Layer Super Output Areas

MPAN Meter Point Administration Number

NCRM Newcastle Carbon Route Map

NCRF Newcastle Carbon Route Framework

NEED National Energy Efficiency Data-Framework

SAP The Standard Assessment Procedure

SCU whole building self-contained unit

SEAPs Sustainable Energy Action Plans

TVRs Thermostatic Radiator Valves

YHN Your Homes Newcastle

data set of rough approximations of household occupancy and three average regional scale landscape and climatic data sets. The NCRM individualized data sets are the dwellings' domestic stock data and building physics data. The coverage of both data sets

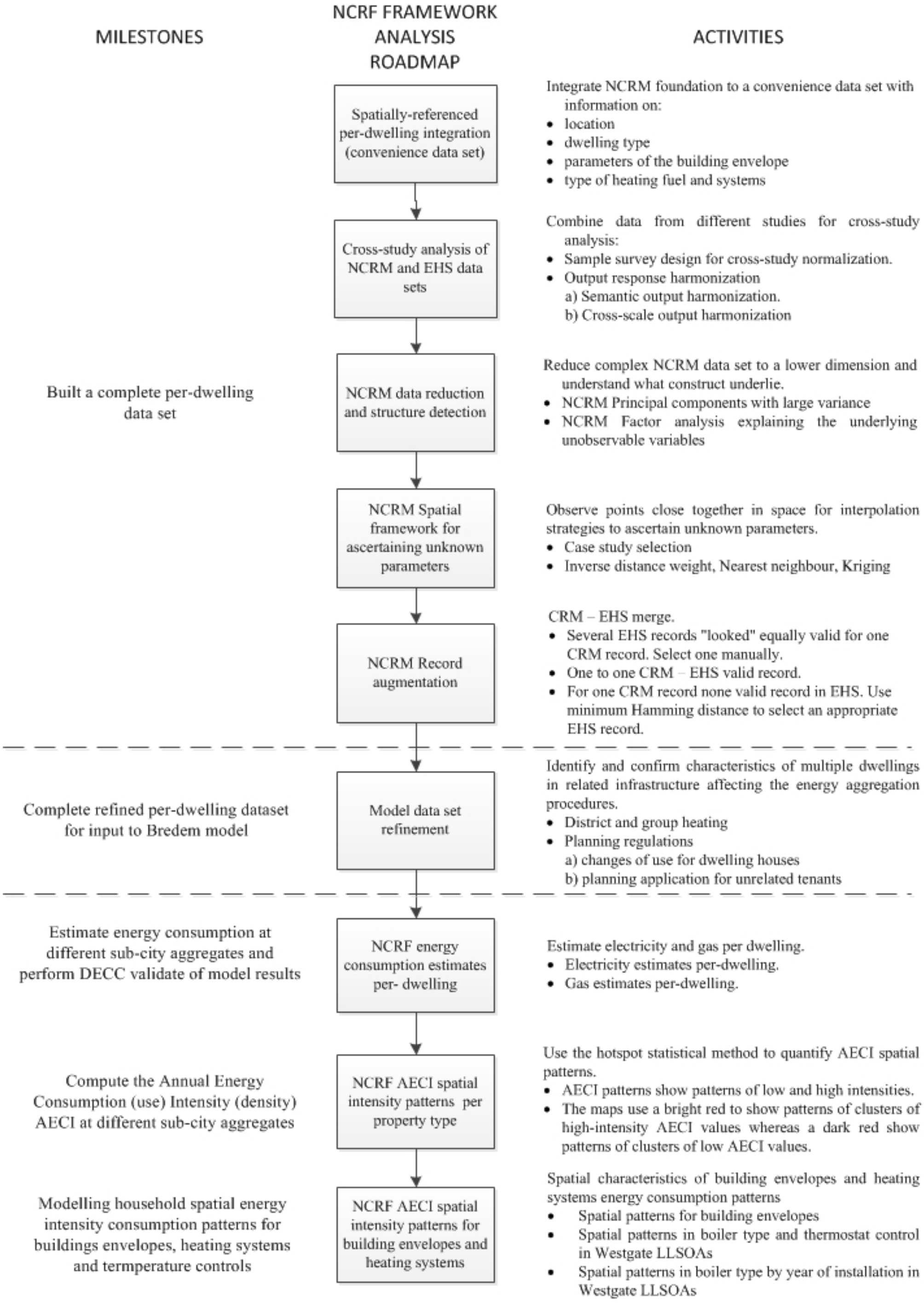

Figure 1: NCRF domestic energy estimation framework

is different; whilst the domestic stock data have 100% coverage, the building's physical data do not. The spatial interpolation strategies are used to complete the missing survey data. Framework assumptions are presented in three sections: Section 2.1 on using Cambridge Housing Model in the framework, Section 2.2 on applying interpolation and imputation methods to NCRM for building a full SAP record, and Section 2.3 on the number of thermal zones for a building. Assumptions on using DECC and the National Energy Efficiency Data-Framework (NEED) as a validator data set are given in Section 2.4.

2.1. The Cambridge Housing Model (CHM)

The CHM is the basis for the per-dwelling energy estimates. However, there are a number of assumptions built into the model that potentially impact on the results of the Energy Modelling Framework. The main assumptions in using the CHM in the framework concern the use of averages for climate data and occupancy.

The CHM [15] relies on regional and monthly climate data as part of the energy use calculations. Additionally, energy outputs are adjusted to match the national statistics in the Digest of UK energy statistics (DUKES) for gas and electricity use since 2009 [15, pp. 14]. This means the same weather adjustment in the monthly external temperature (^{o}C), monthly average wind speed (m/s) and monthly average horizontal solar radiation (W/m^2) are in place for every dwelling in the North East of England, disregarding any possible local microclimates. Urban areas tend to have higher air temperatures than their rural surroundings, as a result of gradual surface modifications that include replacing the natural vegetation with buildings and roads [16]. This is because vegetation [17; 18] plays a significant role in regulating the urban microclimate and can influence domestic energy demand through solar absorption and the cooling effects provided by shade and evapotranspiration. This may mean that areas with a low residential density indicative of more open space require more energy to maintain the same temperature as higher density areas.

Additionally, CHM uses a standard occupancy model, which means a standard number of occupants, i.e., the number of occupants is related to the number of rooms and hence the floor area, and also to standard heating regimes, i.e., the zone one heating times are applied throughout the dwelling for nine hours during weekdays and for 16 hours at the weekend. Assessing household energy requirements using standard occupancy enables comparison of the energy performance of similar dwellings across Newcastle's housing stock. However, standard occupancy does not provide an understanding of the way a household actually uses energy within the dwelling. Actual energy consumption is determined by a wide range of factors beyond simply the physical characteristics of the property. These include socio-demographic, economic, behavioural and practice factors [19; 20; 21] which all influence the amount of energy consumed within a household.

On the whole, the majority of households tend to consume less energy than is estimated by the SAP calculation, especially low energy buildings [22, pp. 6864]. In thermal terms, the worse a home is, the more economically the occupants tend to behave with respect to their space heating; this phenomenon is labelled the pre-bound effect [23, pp. 1270].

In summary, these assumptions in the CHM may be manifest in the energy modelling framework in areas of low residential density, where the energy consumption may be underestimated due to microclimate effects and where there are distinct local idiosyncrasies in the socio-demographic make-up of an area that is divergent from the standard occupancy.

2.2. Assumptions on creating a full SAP record

In Newcastle upon Tyne, the dwelling research population being considered is the city boundaries. The sampling frame is a method of selecting members of the population within that boundary, and in this study the sampling frame is the Warm Zone programme. The overall aim of the Warm Zone programme was to facilitate the efficient, integrated and appropriate delivery of practical measures to alleviate fuel poverty and improve domestic energy efficiency in defined areas. In WarmZone, the sample is 68% of the city dwellings. For these dwelling locations that were not part of the survey, or unvisited dwellings by the Warm Zone programme, several techniques collectively known as spatial prediction methods are used to estimate the values of a particular targeted quantity. Two facts make the spatial interpolation method more adequate prediction method in Newcastle: the WarmZone penetration and the autocorrelation between dwellings in close proximity. First, the WarmZone penetration is high; indeed, there is no MLSOA with unvisited dwellings, i.e., the MLSOA with lowest coverage of dwellings is still significant (South Jesmond 25.32%) and the most visited MLSOA is Blakewell with 84.97%. Second is the first law of geography [24] which indicates "Everything is related to everything else, but near things are more related than distant things". The first law of geography seems to indicate that the urban form shows autocorrelation (correlation with itself relative to proximity /location) i.e,. a best estimation would be obtained using information from neighbouring sites. For these two reasons, the spatial interpolation method is felt to be more appropriate in Newcastle as spatial prediction method. Multiple imputation (MI) [25; 26] is a practical method for valid inferences for unknown values i.e., filling missing data with plausible values. This study uses multiple imputations as a data augmentation procedure in which the Warm Zone Survey records are augmented by EHS records.

The process of creating a full SAP record for use in the CHM is done through record augmentation in a two stage process. The first involves making the best match between a complete NCRM record and an English House Survey (EHS) record, and then copying over unknown fields in the NCRM data set from corresponding EHS fields. The second process involves extending these results to related properties to provide a suitable Standard Assessment Procedure (SAP) record for every dwelling. The main assumptions that underlie these processes are in the spatial interpolation and imputation strategies.

Spatial interpolation introduces uncertainties. The two which are related are the choice of interpolation method and the treatment given to the data outside the edge effect, i.e., in order to fully cover the surface of an interpolated area, some unknown points around the edges of the data set needs to be extrapolated. The third is in the urban penetration of the physical survey.

Record augmentation uses multiple imputations of EHS variables applied to a NCRM individual record to produce an individual, extended NCRM record with full SAP information. The fact that a perfect imputation leading to a single full augmentation with all ten base variables from the initial NCRM record is only possible on, for instance, in 11% in South Heaton district and 1% in Westgate district makes imputation modelling potentially more relevant than interpolation.

In summary, creating a complete full data set of extended NCRM records required a considerable number of refinements in districts where the NCRM has lower penetration and complex infrastructures are in place.

2.3. Assumptions on the number of thermal zones

The number of thermal zones in a building is determined by various factors including building size, shape, orientation, and usage, whereas CHM, the Building Research Establishment Domestic Energy Model (BREDEM) and SAP models use a simplified model for the number of thermal zones. The first zone comprises the major occupied spaces (living area) of a dwelling, while the second zone is the bedroom and the rest of the house. The current assumption in SAP is that the heating thermostat is set to 21^oC and 18^oC in the two zones respectively; however, a default demand temperature of 19^oC is assumed in CHM for the living area and for all dwellings, as opposed to 21^oC in SAP, independent of building massing. Building massing is one of the most important factors in passive solar design, and is one of the most important stages in the design of a building, as the surface areas are exposed to sun at different times of day. In fact, the thermal load and thermal comfort of buildings are affected by a number of factors, among which thermal mass (in particular the thickness of the concrete slab), insulation level, absorption of solar radiation of the exterior walls/roof, and glazing ratio (also known as the window-to-wall ratio) are four factors that have important impacts [27].

This assumption significantly reduces the amount of time required for energy modelling by simplifying the internal layout of the building. In CHM, the internal spaces of every dwelling in a linear block of terrace houses and tall buildings are divided into zones, and there is no difference in their usage and activity, heat gains and losses characteristics, heating systems and operational regimes. Internal layout or thermal zoning has not been considered as an uncertainty variable [28] in other domestic energy models which focus on energy performance assessment using steady-state models [29]. CHM [30] does not consider the number of thermal zones as one of the 31 most sensitive parameters in the local sensitivity study. However, [31, pp. 1190] found the impact of this model simplification to have a mean (absolute) error across diverse buildings of 10.6% for annual heating demand.

In the NCRM/CHM modelling, for instance, a linear block of terrace houses ignores the heat flow from one terrace to the adjacent terrace, i.e., it was relatively safe to assume that the temperatures in the houses on either side were be roughly the same as that in the modelled house, so the thermal transfer through these side walls was likely to be negligible compared to the losses and gains from the outside environment. This means that there is no net flow of heat in either direction, or the dividing walls between two adjacent terraces were adiabatic. A similar condition occurs in the model of a single floor in the middle of a high-rise building.

In the UK, the Dwelling Fabric Energy Efficiency (DFEE) methodology was adopted within the Code for Sustainable Homes (November 2010 version). DFEE methodology [32] considers the space heating demand of a dwelling as being affected by: building fabric U-values, thermal bridging, air permeability, thermal mass, and features which affect lightning and solar gains [32]. In particular for buildings containing multiple dwellings, AECOM showed the air permeability of the full DFEEs drop from 5.2 ($m^3/hr/m^2$ 50Pa) for a three dwelling terrace to 4.8 ($m^3/hr/m^2$ 50Pa) for a seven dwelling terrace.

AECOM suggests that air permeability affects the space heating demand of mid-terrace dwellings such as the ones in South Heaton district, where there is a high concentration of multiple dwelling terrace houses. As an example, Figure 2 shows terraces along Simonside Terrace and Rothbury Terrace.

In summary, the BREDEM model treats dwellings as individual entities and does not take into account adjacent dwellings with shared party walls and floors. The potential heat gain from these buildings is not estimated in the BREDEM model and hence NCRF may overestimate energy in building types like linear terraces where this effect may be

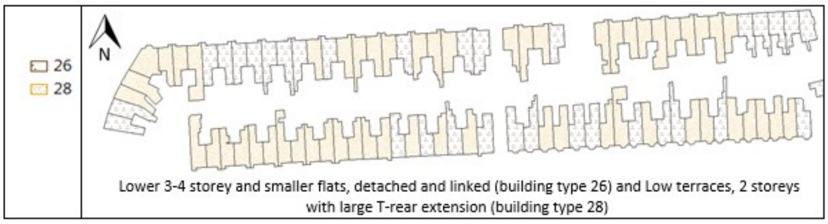

Figure 2: Linear terraces in South Heaton

measurable. In reality, there is an increased heat loss due to air leakage through exterior envelopes as well as the interior partition walls, ceilings and floors [33, pp. 97], therefore, heating energy is needed to offset the heat loss [34]. However, the number of thermal zones will vary depending on many factors including the building use, size, and shape, where a 'zone' is a segment of a building with similar thermal requirements serviced by the same mechanical equipment and controls. On the number of thermal zones, a thermal simulation requires more specific inputs, windows have to be modelled explicitly and the building volumes need to be discretised more finely into thermal zones [35].

2.4. DECC and NEED data as a validating data set

Another potential source of difference between DECC consumption aggregates and NCRF energy output may be attributed to underlying differences or potential inaccuracy within the DECC aggregate data. The main discrepancies are electricity and gas meter count [36], properties not being connected to the gas grid, the DECC domestic/industry threshold, bulk power agreements, and weather correction methodology.

- To produce the electricity consumption aggregated estimates, annualised consumption data were provided to DECC at Meter Point Administration Number (MPAN) level by the data aggregators (DAs). DAs are agents of the electricity suppliers, who collate/aggregate electricity consumption levels from each electricity meter. MPAN consists of approximately 80 per cent actual ('Annual Advance') readings and 20 per cent estimated readings ('Estimated Annual Consumption'). In addition, electricity consumption data for each MPAN is not weather corrected.

Furthermore, the sum of meter points for domestic energy consumption at MLSOA level does not always equal the sum of meter points for domestic energy consumption at the associated levels due to missing or incorrect address information or an unallocated load.

- [37] identify areas and types of properties off the gas grid. It shows that purpose-built flats are the least likely to have a gas meter. The NEED data also suggest that,

  > *small modern properties are the least likely to have a gas connection, for example, 70 per cent of post 1999 flats have no gas connection. It is likely the majority of these properties without gas are in areas which are on the gas grid, but with no gas connection in the property (e.g., blocks of flats in high density urban areas). The data also show that more generally, the largest and smallest properties are least likely to have a gas connection, for example 43 per cent of properties with a floor area of more than 200 square metres and 42 per cent of properties with a floor area of 50 square metres or less have no mains gas in the home; compared with the average for all properties of 18 per cent [37, pp. 74].*

  Properties in Westgate LLSOAs 8397 (58.08%), 8440 (66.55%) and 8349 (37.78%) are off the gas grid properties, and are therefore not included in the DECC gas statistics but through interpolation are included in the NCRM data set.

- DECC sub-national statistics use an industry cut off of 73,200kWh to determine whether a gas meter is domestic or not, with all meters with consumption of 73,200kWh or below assumed to be domestic. This means a number of smaller commercial/industrial consumers are allocated as domestic and therefore the estimates of the percentages of households without gas is an underestimate of the true number.

- Your Homes Newcastle (YHN) tenants are billed directly for energy use, except in properties supplied by district and group heating networks (charged by a fixed tariff). YHN and Newcastle City Council purchase the fuel for district and group heating in bulk, together with the other councils in the North East. DECC statistics (which reports individual meter readings) do not include these properties.

- DECC [38, pp.10] gas sub-national consumption figures have been weather corrected, whereas electricity consumption figures are estimates of actual consumption and have not been weather corrected. The DECC annualised and weather corrected Meter Point Reference Number (MPRN-level) gas consumption data are obtained from XoServe. The [39, pp. 28] apply the weather correction to the data prior to it being supplied to XoServe and DECC. Although a certain amount of information relating to the DECC process of annualisation and weather correction is available, the effect that this process has on modifying the gas values, and therefore the impact that the factoring has on the final results of analysis, is not fully known. This process of weather correction [40] is therefore impossible to reverse based on information currently in the public domain and introduces unknown effects into the available annualised records for each individual house that cannot be interrogated. In the case of NEED gas consumption data, these are weather-corrected by the Energy Companies before being submitted as annual data to DECC.

  NCRF uses CHM for estimating the annualised gas consumption. CHM Outputs [41, pp.3] are also adjusted to match DUKES data for gas and electricity use each year. This means that effectively it also includes a weather-adjustment. The key modification in CHM is the use of 19^{o}C (292K) as the baseline demand temperature for the living area for all dwellings SAP uses 21^{o}C. In CHM, a normalized sensitivity coefficient (Si) is computed to consider the impact on the total energy consumption of small changes to internal demand temperature model parameters xi, as shown in Equation 1. This section uses the [30] one-at-a-time approach i.e., changing input parameters individually while holding the others constant and assessing the effect on outputs.

$$Si = \frac{dy}{dxi}\frac{xi}{y} \tag{1}$$

Where (xi) represents the original value of the internal demand temperature (K) model parameter, (y) represents the original total energy consumption, and (Si) represents the sensitivity of the model output to parameter variations around the best estimate values. The normalized Si equals 23.31 [30, pp. 159] for variations in the internal demand temperature individually, while holding constant the others parameters affecting the energy demand. By choosing dxi to represent a 1% variation in xi, Si represents the percentage change in total energy due to a 1% change in the model parameter (e.g., the original demand temperature is 292.15K or 19^{o}C; a 1% variation expressed in Kelvin equates to a variation of 2.92K, while for ^{o}C it equates to 0.19^{o}C). A variation of 5.2632% expressed in ^{o}C equates to a variation of 1^{o}C and the value for dy/y is then equal to 1.2268. In Castle, the results show a change in the demand for gas to 99,419,327kWh (from an original value of 44,646,725kWh), and for electricity to 25,998,546kWh (from an original value of 11,675,295kWh). The internal demand temperature is by far the most significant parameter in the CHM modelling process, i.e., for a 1^{o}C increase in the internal demand of temperature; there is an increase of 122.68% in the energy consumption.

In summary, different weather correction methodologies in DECC/NEED and CHM lead to some discrepancies, which probably vary somewhat from year to year. The main reason for this is that the exact methodology for weather correction for NEED/DECC is not fully disclosed.

This section has summarised some of the key assumptions that need to be considered when comparing NCRF energy outputs with DECC and NEED data. The actual effect of any individual issue is difficult to quantify but detailed analysis may provide some areas for further discussion.

3. The energy efficiency policy

The Energy Efficiency Directive (EED) [42] establishes a common framework of measures for the promotion of energy efficiency within the European Union (EU). The four important measures are: first, that energy companies are requested to reduce energy sales by 1.5% every year among their customers by improving the heating systems, the double-glazing in windows, or insulating the roof; second, the public sector is required to renovate 3% of buildings, i.e., every year, EU countries are required to renovate at least 3% of the total floor area of buildings owned and occupied by central government; third, EU countries are requested to elaborate a roadmap to make the building sector more energy efficient by 2050, and, fourth, energy plans are required for large companies (which includes cost-benefit analysis) for the deployment of Combined Heat and Power (CHP). Four EED articles are relevant to this paper: Articles 9, 10, 11 and 14. Article 9 requires that member states ensure that final customers of electricity, natural gas, district heating and cooling and domestic hot water (extended also to final customers residing in multi-apartment and multi-purpose buildings with a common central heating) are provided with competitively priced individual meters that accurately reflect the final actual energy consumption and the actual time of use. Article 10 requires that billing information based on actual consumption be available at least quarterly, while Article 11 requires that metering and billing information as well as bills be provided free of charge to the final customer. Additionally, all countries are required to use energy more efficiently at all stages of the energy chain —from the transformation of energy and its distribution to its final consumption. The directive also establishes an indicative national energy efficiency target for 2020. Finally, Article 14 (promotion of efficiency in heating and cooling) means in the UK that LAs will issue permits for installations satisfying the above definitions in the range 20MW $\leq$ Thermal Input $<$ 50MW, whereas the Environment Agency (e.g., in England) will issue permits for installations satisfying the above definitions in the range of Thermal Input $\geq$ 50MW.

DECC [43] implements the EED in the UK, ensuring that developers of new generation installations over 20MW undertake a cost-benefit analysis of the case for developing a "Good Quality CHP". In the domestic sector, the estimated cost-effective potential for CHP supplying small Heat Networks in 2020 is 1,975MW with up to 6MW electrical capacity in size [44]. LAs are enabled to take pre-commercial development of heat networks through a Heat Networks Delivery Unit (HNDU) [45]. However, there are three issues around Heat Network development: the lack of common technical standards, the lack of statutory access to land, and difficulties joining up networks. Furthermore, [46] argue that the willingness of homeowners to replace their heating systems depends on the size of the property and being in the grid or not. For example, homeowners living in smaller properties are concerned about the size of the heating system, and the amount of space needed for any additional parts (or eventually the fuel storage); therefore, it is less likely that Ground Source Heat Pump (GSHP) or a biomass boiler is an option, whereas off-gas grid homeowners living in detached properties are more likely to select a GSHP or biomass boiler. Off-gas grid homeowners living in flats are more likely to select a heat network, whereas on-grid homeowners in general prefer condensing boilers.

The government implemented first a consultation for the EED as it applies to metering and billing of heating and cooling [47]. Later, the Heat Network (Metering and Billing) Regulations (2014) implements the requirements of the EED in Britain. The EED repeals the Cogeneration [48] and the Energy End-Use Efficiency and Energy Services [49].

All central heating systems can be fitted with some method of temperature control but the sensitivity and flexibility of these controls can vary. The two main types of control relate the timing of the system and the adaptability of the system to room temperature: first the programmable Heating, that are individual room-heaters that may be automatically operated by timers (for example a storage radiator); and second, individual room-heaters that may not be automatically operated by timers (an example is a portable electric heater). Other subdivision is fixed and non-fixed (i.e., portable) heaters.

4. Spatial characteristics of heating systems energy consumption patterns

This section analyses the spatial characteristics of the energy consumption patterns of building envelopes and heating systems (i.e., insulation, efficiency, age) in communities in Britain, in particular communities in Newcastle upon Tyne. We argue that a better understanding of the observed spatial variation and distribution in domestic energy consumption in communities could be helpful in facilitating the management of domestic energy systems across cites. This section uses the social housing in the Newcastle's Westgate LLSOAs 8399 and 8439 communities in the analysis. Westgate has an area of 501 hectares and contains the commercial centre of the city; is the main transport interchange for the city, and has a high concentration of residential self-included dwellings and mix-use buildings.

The four maps in Figure 3 show social housing stock over a yellow graduated energy consumption intensity background. Map (a) represents the total social housing stock (in cyan) and the spread in terms of number of bedrooms is described in three adjacent figures: (b) shows social houses with a single bedroom, (c) shows those with two bedrooms, and (d) those with three bedrooms. The intense yellow in Figure 3 corresponds to areas with higher energy consumption. Single bedroom areas correspond to the areas in Campbell Place in the red rectangle in (b), while two and three bedrooms corresponds to the areas in Monday Crescent in the black rectangle in (c) and (d).

Monday Crescent in the black rectangle is in an area of high energy consumption (intense yellow in the (a) map) presumably because 35% of the houses (the majority are two storey mid-terraced and some semi-detached) are uninsulated and 43% use a standard boiler. In the two bedrooms (c) map, 64% are uninsulated and 50% use standard boilers, and in the three bedrooms (d) map, 33% are uninsulated and 43% use a standard boiler.

The red rectangle in map (b) of Figure 3 shows the one bedroom (also one storey building) housing in Campbell Place. This map is also an area of high energy consumption (see the intense yellow in the background). The local area characteristics of Campbell Place correspond to mid-terraces where 98% are uninsulated and 83% use an

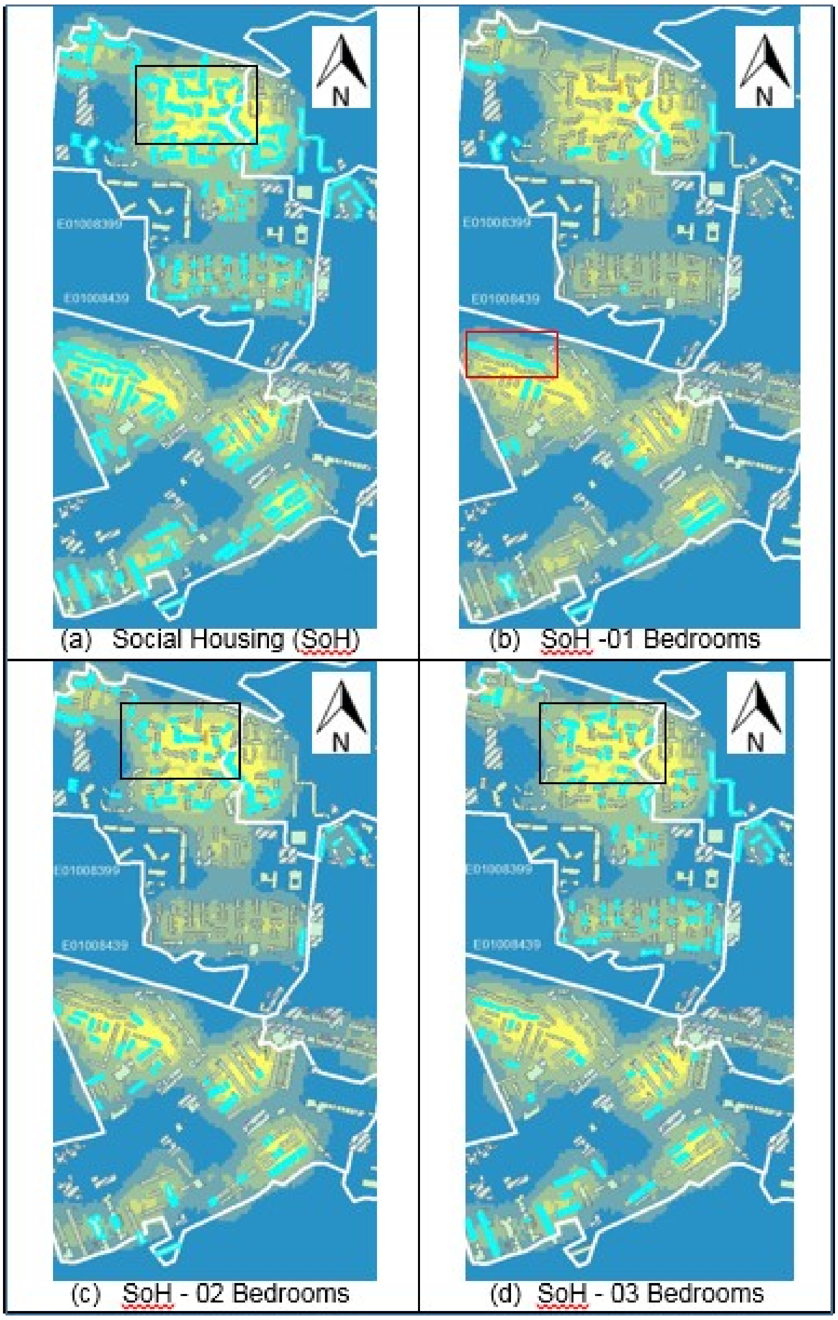

Figure 3: Number of bedrooms in Westgate LLSOAs at scale 1:7,000

inefficient standard boiler.

The maps of Figure 3 suggest that local area characteristics are important when systematically establishing energy baseline consumption for specific sub-city geographical areas. This approach through the NCRF provides the potential for energy planners and other bodies to model energy interventions with flexibility in scale and to potentially adapt plans to local area characteristics. One interesting application is the [50] Community Right to Build, that allows local communities to propose small-scale, site-specific, community-led developments that are important to them. It came into effect on 6 April 2012. Relevant renewable energy developments could include Installing solar PV panels, development of a community-owned wind turbine or hydro-electric system, building a boiler room and feed store for a biomass boiler, constructing a district heating network for a town centre or network of homes. Subsequently, we believe 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.

Figure 4 shows the boiler type in Westgate LLSOAs 8399 and 8439. The (a) map shows houses with combinational boilers, the (b) map shows houses with communal heating, the (c) map shows houses with a programmable heating control and the (d) map heating houses with control programmer with room thermostats. All maps share an increased intensity yellow, showing the areas of high energy consumption.

The space heating for the Monday Crescent dwellings are water-filled pipes and radiators running from a combinational boiler (see the (a) map black rectangle). The dwellings include three types of heating controls: the dwellings in the (c) map have a timer or programmer (61.62% of the total), the dwellings in the (d) map have a room thermostat (34.88% of the total) which allows setting different temperatures for different times of the day, and the rest (3.48%) of the dwellings use thermostatic radiator valves (TRVs) on individual radiators which allow different temperatures in individual rooms. TRVs reduce the flow of water to the radiator and do not control the boiler.

Shipworth et al. [51] have argued that central heating thermostats do not reduce the

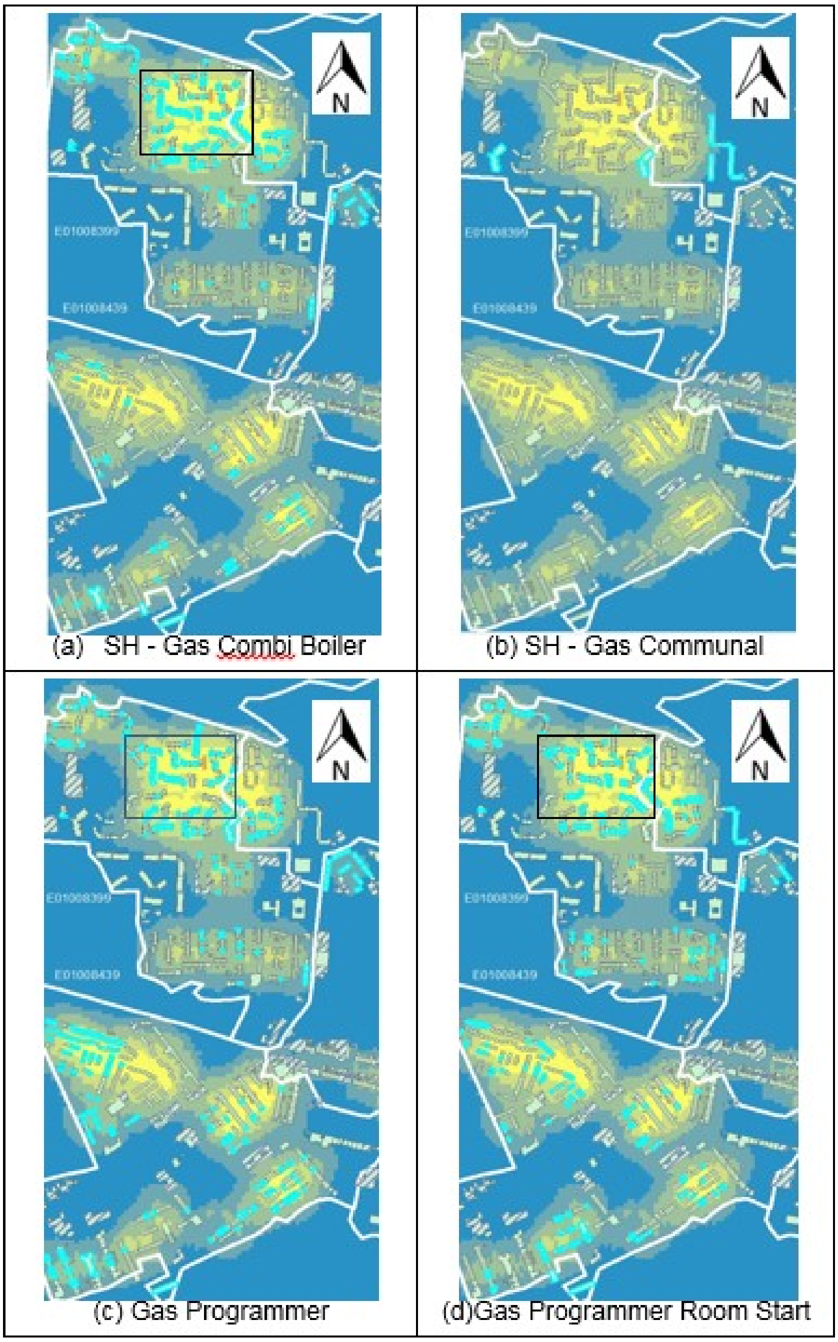

Figure 4: Boiler type and thermostat control in Westgate LLSOAs at scale 1:7,000

average maximum living room temperatures or the duration of operation. Interestingly, the code of good practice 302 [52, pp. 5] suggests that controls do reduce higher room temperatures and further a reduction of space heating consumption by 6 to 10% can be obtained by turning down the thermostat in one degree Celsius. However, while the thermostats capabilities to control temperature are well understood, less is known about the effectiveness of the technologies devised to enable energy savings [53]. Interestingly, in (c) and (d) maps there is no clear evidence in NCRF of a significant effect on the annual gas consumption by introducing different heating controls. This is a direct consequence of the two main drawbacks of physical models that behaviours are averaged and temperatures are assumed. In behaviour models, behaviour is at least as important as other factors for explaining dwelling energy consumption. [54] argue that behaviour has a significant influence space heating and electricity and a less significant influence in water heating. But perhaps the major difficulty of NCRF physical modelling is that internal temperature is a constant, and if all other factors being constant, variations in internal temperature is the most sensitive parameter in energy demand [30, pp. 159]. Additionally Figure 4 also shows the more efficient communal heating in the (b) map and the less efficient combinational boilers are in the (a) map. The (b) map shows a group of building with combinational boilers in areas of high AECI whereas in the (a) map the buildings using communal heating are in areas of low AECI.

Figure 5 shows Westgate LLSOAs 8339 and 8430, in the (a) map the standard boiler and in (b) the warm air heating system.

In the Figure 5, the black rectangle in the (a) map is an area made up of standard boilers in planned balanced-mixed estates (1964-1979) with large buildings, whereas the black rectangle in the (b) map shows the warm air system in the newer, smaller terraced buildings (1945-1964). Warm air systems could potentially create draughts in the house and some of these systems have a limited control of the internal temperature due to the lack of room thermostats and thermostatic radiator valves. Currently, the Energy Performance Certificate (EPC) recommends changing warm air units to biomass boilers due to maintenance costs.

In summary, the boiler type, heating controls and the tenure type follows a spatial distribution. Although the data collection and modelling has significant uncertainties

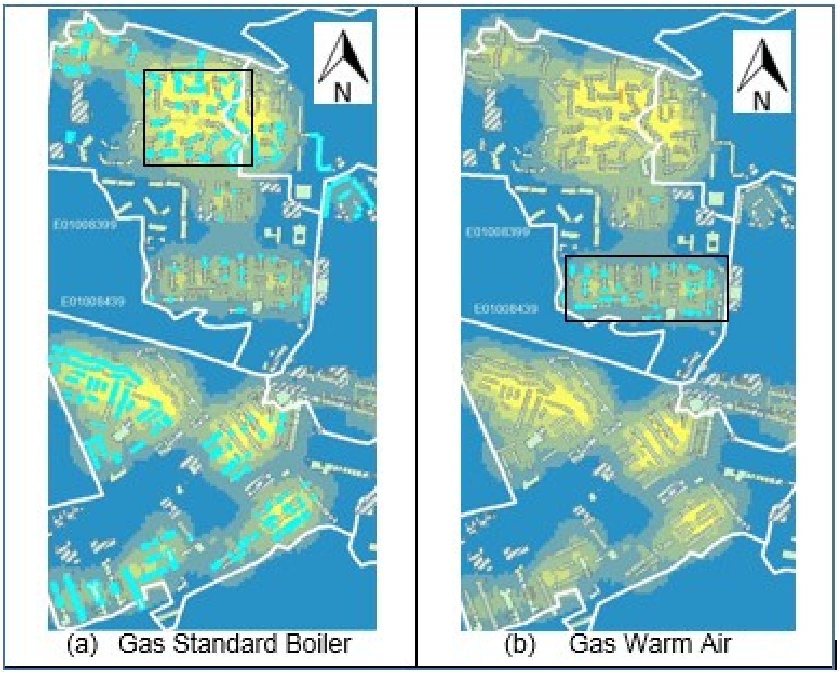

Figure 5: Boiler type by year of installation in Westgate LLSOAs at scale 1:7,000

associated with individual building energy estimates, this approach does seem to enable us to analyse and visualise spatial and other patterns in the data at certain scales that capture a reasonable facsimile of the physical properties of the buildings and their energy Standard Assessment Procedure (SAP) profile. This allows us to pose some questions about appropriate retrofit measures and other matters related to energy consumption. The next two paragraphs show statistics which may support such a new approach.

As of 31st December 2013 [55] 129,842 Green Deal assessments had been made in Great Britain, of which 75% of the valid assessments were on owner-occupied properties. The Green Deal scheme provides finance to make energy-saving improvements in a home and finds the best way to pay for them. It is a scheme which allows homeowners (and tenants) to install energy efficiency measures with no up-front cost.'

The relevant improvements recommended were boiler (upgrade) (13.2%), cavity wall insulation (13.2%), loft insulation (15%), micro generation (16.2%), and solid cladding (10.6%), and usually two to three improvements were recommended per assessment.

Regionally, the number of assessments in the North East were low, as from 3,976 (3.06% of the total) only 280 (0.22% of the total) were made in Newcastle upon Tyne. The number of live Green Deal plans in Newcastle was only four out of 100 in Great Britain. The provisional number of properties with energy efficiency work delivered under Core Cities Project in Newcastle was only 137, with the number of measures installed being 312.

An area-based approach allows more houses to be targeted in places where local area characteristics show inefficient elements, and may therefore potentially capture a greater number of fuel poor households per unit of cost, compared to the existing self-referral method, e.g., Green Deal. Refurbishing South Heaton Victorian houses with external solid wall insulation thus has several benefits. [56] argues that the refurbishment of solid walled houses can achieve SAP ratings equal to or better than those of new build properties complying with building regulations by adopting such measures as: 'loft insulation, insulated dry lining to external walls, or external insulating render, ground floor insulation, secondary glazing, gas central heating with condensing boiler, controlled ventilation system', and this may increase the rental income among other benefits not related to energy efficiency. Also, [57, pp.19] argues that the main emphasis of the Housing Market Renewal Pathfinders Programme was on 'preserving and improving the existing housing stock wherever possible. Innovative approaches to the refurbishment of Victorian terraces in order to retain the original character of the neighbourhoods wherever this was practical.'

Should measures be applied today to low income households, this may prevent them falling into fuel poverty in the future due to changes in the house condition. Moreover, providing measures for each one in an area impacts on the health and wellbeing of all, hiding the perceived individual poverty stigma of a fuel poverty measure.

Using this type of analysis, the approach to energy efficiency areas may exploit a similar concept as that used in the fuel poverty literature known as the Low Carbon Zone (LCZ) [58]. In this approach, all the residents within the area may be offered a (ECO) package to improve the energy efficiency of the home without considering the tenure or income of the household. Nowadays, the Green Deal does not use this area approach by concentrating on the most appropriate measure according to the building type, and thus it may not be working as it should.

5. Discussion

This paper has shown that city records can be used to improve the data quality in the modelling framework because local authorities have extra information to help with the validation process. The modelling framework uses the CHM to estimate the energy consumption in individual dwellings. The initial variables of the energy profile are: usable floor area, dwelling type, construction date, number of floors above ground, predominant type of wall structure, cavity wall insulation, main heating fuel, primary heating system, boiler group and tenure.

Tenure correlates strongly with the heating system and owner occupied and social housing are the predominant tenures. Communal heating and E7 is focalized in social housing rented properties from local authority and housing associations, whereas gas heating is mostly in owner occupied and private rented properties. E7 is an electricity tariff, meaning that the user pays a different price for electricity at different times of day. With an E7 tariff, the electricity used at night costs less than the electricity used during the day. It is called E7 because it gets cheaper electricity for 7 hours each night. E7 use a different kind of meter, which, unlike a standard meter, can read the electricity it uses during the day and night separately.

There are more installations of efficient boilers in owner occupied tenures than in private rented. The result suggests that social housing is the most efficient stock and private rented the least. However, for the rented and owner occupied tenures the Warm Front scheme (WF) provides grants for packages of insulation and heating improvements including central heating systems.

District heating (DH) is a rational way to supply domestic heating and hot water to buildings in densely heated[1] areas where it is reasonable to connect to low-energy dwellings. District heating (heat network) in the UK is a small sector. [45, pp. 14] estimate around 2% of domestic of the UK heat demand is supplied via heat networks. However, it was difficult to say how many dwellings are served by individual heat meters. [45, pp. 15] estimate that approximately 25% of existing residential-led heat networks schemes have heat meters installed (the charging mechanisms for the remaining 75% are based upon apportionment or a points-based system). One possible direction for LAs is to take a pre-commercial development of heat networks through a Heat Networks Delivery Unit (HNDU) [47]. Also, the government implemented first a consultation for the EED as it applies to metering and billing of heating and cooling [59]. Later, the [60] implemented the requirements of the EED in Britain. [61, pp. 27] argues that the cost of connection varies across built forms with the lower costs (infrastructure and connections) are for low-rise flats, high-rise flats, converted flats and small terraced. The impact of district heating in Westgate is important. Westgate LLSOAs 8395 and 8439 have, respectively, 16% and 43% dwellings with district heating as the primary heating arrangement because it has relative high proportions of terraced houses and high rise buildings. The Westgate LLSOA 8395 houses the YHN Queens Court biomass (wood pellet burning) district heating feeding 120 high-rise dwellings whereas the Westgate LLSOA 8439 houses the YHN St. Annes Close district heating feeding 190 mid-rise terraced dwellings. One possible drawback of DH structure is that it is not possible to obtain individual gas consumption because not every household has an individual heat meter. BRE [62] argues that the installation of heat metering is not cost-effective from the perspective of an individual consumer. Additionally, none of the bottom-up or top-down models that are used by the European Commission are suited to addressing the spatial elements needed to model the development of a network infrastructure or an eventual competition in the market for space heating between natural gas, cogeneration of electricity and heat (CHP) or district heating. Thus, a detailed building description

[1] Heat density is the amount of heat required per m^2 of land or per pipe length.

with spatial components (e.g., to automatically calculate building volumes) and models that describe the household real characteristics need to be part of a strategic framework for low carbon heat in the UK.

The NCRF has underestimated this consumption by making assumptions in aggregating a group of bedsits to a single 'self-included synthetic dwelling' with a reduced number of thermal zones. This paper has used approximations of the modelling of bedsits with shared amenities in houses and flats depending on whether it uses the entire house or shares a portion of it. This assumption underestimates the energy consumption because all rooms are heated with different heating patterns, i.e., all rooms are a different thermal zone and overheating may exist.

One possible solution to overheating is to provide individual room temperature control through thermostatic radiator valves (TRVs) for the system to maintain balanced temperatures around the house, tests carried out by Salford University [63] suggest this possibility. In the use of TRVs, [64] argue that when "all of the TRVs were kept on the design value, the 'free heat' such as solar radiation could be efficiently used, overheating could be reduced and a considerable energy saving effect could be gained". In Newcastle, citywide use of programmable room thermostats with TRVs occurs in 12% of the dwellings using heating controls. However, Part L of the building regulations requires that only new heating systems would have effective controls. The installation of TRVs in replacing a boiler would be considered good practice and not seen as compulsory in building regulations. One possible solution is to have a model that includes local area characteristics where the heating controls are part of the survey. Evidence shows that it is most likely that a change in heating controls follows a change in boiler; however, HEED data sets do not collect sufficiently detailed data on installation of heating controls [65]. Additionally, there is a need to include in Part L of the Building Regulations in 2016 the installation of mandatory TRVs with a boiler replacement. Also, TRV may be included in the eligible measures in the Green Deal and Energy Company Obligation. Finally, the DECC Heat Strategy: 'The Future of Heating: Meeting the challenge' may also consider the improvement of controls in homes.

The framework results may be useful in providing energy consumption within sub-city areas for local governments. There are policies in place in the UK regarding the responsibilities of Local Authorities' installed capacity, i.e., Local Planning Authorities are responsible for the renewable and low carbon energy development of 50 megawatts or less installed capacity under the [66]. Meanwhile, renewable and low carbon development over 50 megawatts capacity will be considered by the Secretary of State for Energy, under the [67], and the local planning authority will be a statutory consultee. Although this study focuses on energy consumption in sub-city areas, the findings may well have a bearing on altering the energy profile of a group of buildings so that there is potentially a better match between energy demand and the installed supply capacity in a local area community energy planning project.

6. Conclusions

This paper shows the NCRF integration of urban energy models with a spatially enabled database as a key component. This open up an area of research that capture not only the information of the buildings by themselves but the relationships between buildings, and the interaction between different levels of the built environment (e.g., between buildings and streets). NCRF integrates multiple domains, at scales in a common spatially enabled database environment. However, some difficulties have to be overcome, especially the difficulty of obtaining the necessary data for energy modelling research.

Furthermore, this study has proven the benefits arising from this spatially enabled approach. From the spatial analysis, it is possible to use operators and develop queries that enable: first, a comparison of the effect of using different local area characteristics on the patterns extracted, which are potentially useful for energy efficiency measures in sub-city areas; and second, the identification of building aggregated areas with spatial expression patterns most similar to a given parameter within the building energy profile.

Finally, this paper supports LAs and stakeholders to map and model energy demand in sub-city areas in several ways: first, with a flexible building based framework to estimate the energy consumption, that may not follow the traditional population based administrative boundaries (MLSOA, LLSOA and individual properties) where government data is available, but do not match policy or intervention needs. Second, with a methodology to construct a detailed energy profile for individual dwellings, for which data is not always available, and therefore there is a need to convert data from different but overlapping geographies e.g., English Housing Survey. Third, strengthen the available tools that policy-makers and city energy planners may need to identify local priority neighbourhoods, in order to help assess the impact of energy efficiency interventions in these areas.

References

[1] OECD Conference Proceedings. Competitive Cities and Climate Change. Milan: OECD; 2008. Available from: `https://www1.oecd.org/gov/regional-policy/50594939.pdf`.

[2] IEA. Worldwide Trends in Energy Use and Efficiency - Key Insights from IEA Indicator Analysis. Paris, France: IEA Publications.; 2008. Available from: `http://www.iea.org/publications/freepublications/publication/Indicators_2008.pdf`.

[3] Covenant of Mayors. How to develop a Sustainable Energy Action Plan (SEAP) Guidebook. Brussels: European Union; 2010. Available from: `http://www.eumayors.eu/IMG/pdf/seap_guidelines_en.pdf`.

[4] Directive 2010/31/EU. of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union; 2010. Available from: `http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF`.

[5] Taylor S, Fan D, Rylatt M. Enabling urban-scale energy modelling: a new spatial approach. Building Research & Information. 2013;42(1):4 – 16.

[6] Steadman P, Hamilton I, Evans S. Energy and urban built form: an empirical and statistical approach. Building Research & Information. 2013;42(1):17 – 31.

[7] Mrz S. Assessing the fuel poverty vulnerability of urban neighbourhoods using a spatial multi-criteria decision analysis for the German city of Oberhausen. Renewable and Sustainable Energy Reviews. 2018;82:1701 – 1711. Available from: http://www.sciencedirect.com/science/article/pii/S1364032117310651.

[8] Hargreaves A, Cheng V, Deshmukh S, Leach M, Steemers K. Forecasting how residential urban form affects the regional carbon savings and costs of retrofitting and decentralized energy supply. Applied Energy. 2017;186:549 – 561. Sustainable Thermal Energy Management (SusTEM2015). Available from: http://www.sciencedirect.com/science/article/pii/S0306261916302513.

[9] Albrechts L, Healey P, Kunzmann KR. Strategic Spatial Planning and Regional Governance in Europe. Journal of the American Planning Association. 2003;69(2):113–129. Available from: https://doi.org/10.1080/01944360308976301.

[10] Calderon C, James P, Urquizo J, McLoughlin A. A GIS domestic building framework to estimate energy end-use demand in UK sub-city areas. Energy and Buildings. 2015;96:236 – 250. Available from: http://www.sciencedirect.com/science/article/pii/S0378778815002212.

[11] Urquizo J, Calderón C, James P. Understanding the complexities of domestic energy reductions in cities: Integrating data sets generally available in the United Kingdom's local authorities. Cities. 2018;74:292 – 309.

[12] Heinonen J, Junnila S. Residential energy consumption patterns and the overall housing energy requirements of urban and rural households in Finland. Energy and Buildings. 2014;76:295 – 303. Available from: http://www.sciencedirect.com/science/article/pii/S0378778814002163.

[13] Parshall L, Gurney K, Hammer SA, Mendoza D, Zhou Y, Geethakumar S. Modeling energy consumption and CO2 emissions at the urban scale: Methodological challenges and insights from the United States. Energy Policy. 2010;38(9):4765 – 4782. Special Section on Carbon Emissions and Carbon Management in Cities with Regular Papers. Available from: http://www.sciencedirect.com/science/article/pii/S0301421509005163.

[14] Calderón C, James P, Alderson D, McLoughlin A, Wagner T. Data availability and repeatability for urban carbon modelling: a CarbonRouteMap for Newcastle upon Tyne. In: Retrofit 2012. Manchester England; 2012. Available from: http://www.energy.salford.ac.uk/page/day_2_papers.

[15] Hughes M. A guide to the Cambridge Housing Model. Department of Energy and Climate Change; 2011. Available from: https://www.gov.uk/government/statistics/cambridge-housing-model-and-user-guide.

[16] Urquizo J, Calderón C, James P. Metrics of urban morphology and their impact on energy consumption: A case study in the United Kingdom. Energy Research & Social Science. 2017;32:196 – 212.

[17] Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy. 2001;70(3):295 – 310.

[18] Akbari H, Konopacki S. Calculating energy-saving potentials of heat-island reduction strategies. Energy Policy. 2005;33(6):721 – 756.

[19] Druckman A, Jackson T. Household energy consumption in the UK: A highly geographically and socio-economically disaggregated model. Energy Policy. 2008;36(8):3177 – 3192. Available from: http://www.sciencedirect.com/science/article/pii/S0301421508001559.

[20] Andersen RV, Toftum J, Andersen KK, Olesen BW. Survey of occupant behaviour and control of indoor environment in Danish dwellings. Energy and Buildings.

2009;41(1):11 – 16. Available from: http://www.sciencedirect.com/science/article/pii/S0378778808001655.

[21] Abrahamse W, Steg L. Factors Related to Household Energy Use and Intention to Reduce It: The Role of Psychological and Socio-Demographic Variables. Research in Human Ecology. 2011;18(1):30 – 40.

[22] Kelly S, Crawford-Brown D, Pollitt MG. Building performance evaluation and certification in the UK: Is SAP fit for purpose? Renewable and Sustainable Energy Reviews. 2012;16(9):6861 – 6878. Available from: http://www.sciencedirect.com/science/article/pii/S1364032112004595.

[23] Sunikka-Blank M, Galvin R. Introducing the prebound effect: the gap between performance and actual energy consumption. Building Research & Information. 2012;40(3):260–273. Available from: https://doi.org/10.1080/09613218.2012.690952.

[24] Sui DZ. Tobler's First Law of Geography: A Big Idea for a Small World? Annals of the Association of American Geographers. 2004;94(2):269 – 277.

[25] Rubin DB. Multiple Imputation after 18+ Years. Journal of the American Statistical Association. 1996;91:473–489. Available from: http://www.tandfonline.com/doi/abs/10.1080/01621459.1996.10476908.

[26] Schafer JL, Olsen MK. Multiple Imputation for Multivariate Missing-Data Problems: A Data Analyst's Perspective. Multivariate Behavioral Research. 1998;33(4):545–571. PMID: 26753828. Available from: http://dx.doi.org/10.1207/s15327906mbr3304_5.

[27] Zhu Y. Built environment. China Architectural Engineering Industrial Publishing Press; 2016.

[28] Urquizo J, Calderón C, James P. Using a Local Framework Combining Principal Component Regression and Monte Carlo Simulation for Uncertainty and Sensitivity

Analysis of a Domestic Energy Model in Sub-City Areas. Energies. 2017;10(12):1 – 22.

[29] Firth SK, Lomas KJ, Wright AJ. Targeting household energy-efficiency measures using sensitivity analysis. Building Research & Information. 2010;38:25 – 41.

[30] Hughes M, Palmer J, Cheng V, Shipworth D. Sensitivity and uncertainty analysis of England's housing energy model. Building Research & Information. 2013;41(2):156 – 167. Available from: http://www.tandfonline.com/doi/abs/10.1080/09613218.2013.769146.

[31] Korolija I, Zhang Y. Impact of model simplification on energy and confort analysis of dwellings. In: Proceedings of BS2013: 13th Conference of IBPSA.; 2013. Available from: http://www.ibpsa.org/proceedings/bs2013/p_1502.pdf.

[32] AECOM. Fabric Energy Efficiency for Part L 2013. Classification methomethod for different dwelling types. Zero Carbon Hub; 2012. Available from: http://www.zerocarbonhub.org/sites/default/files/resources/reports/Fabric_Standards_for_2013-Worked_Examples_and_Fabric_Specification.pdf.

[33] Kusuda T. Fundamentals of Building Heat Transfer. Journal of Research of the National Bureau of Standards. 1977;82(2).

[34] Lindberg R, Korpi M, Vinha J. Factors affecting energy consumption of buildings. Building Enclosure Science & Technology.; 2008. Available from: http://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/BEST1_022.pdf.

[35] Dogan T, Reinhart C, Michalatos P. Automated multi-zone building energy model generation for schematic design and urban massing studies; 2014.

[36] DECC. Domestic Energy Consumption. Department of Energy and Climate Change; 2008. Available from: http://www.neighbourhood.statistics.gov.uk/dissemination/MetadataDownloadPDF.do?downloadId=26286.

[37] DECC. Special feature NEED analysis: Areas and types of properties off the gas grid. Department of Energy and Climate Change; 2013. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/267375/off_gas_grid.pdf.

[38] DECC. Sub-national consumption statistics: Methodology and guidance booklet (URN 12D/473). London: Department of Energy and Climate Change; 2014. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/359302/subnational_methodology_and_guidance_booklet.pdf.

[39] National Grid. Gas Demand Forecasting Methodology. National Grid plc; 2012. Available from: http://www.nationalgrid.com/NR/rdonlyres/71CFD0F6-3607-474B-9F37-0952404976FB/52071/GasDemandForecastingMethodologyFeb12.pdf.

[40] Hamilton SPLRSAJ I G, Bruhns H. Report on the exploratory analysis of the Homes Energy Efficiency Database and Energy Demand. Buildings and Energy Data Frameworks UCL Energy Institute.; 2011. Available from: http://www.bartlett.ucl.ac.uk/energy/research/themes/buildings/building-and-energy-data-frameworks.

[41] Palmer J, Tillson A, Armitage P. Comparing the Cambridge Housing Model against the National Energy Efficiency Data-Framework and Meter Readings. Cambridge Architectural Research; 2013. Available from: https://www.gov.uk/government/publications/comparing-the-cambridge-housing-model-against-the-national-energy-efficiency-data-framework-and-meter-readings.

[42] Directive 2012/27/EU. of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (Text with

EEA relevance). Official Journal of the European Union; 2012. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:EN:PDF.

[43] DECC. The Energy Efficiency Strategy: The Energy Efficiency Opportunity in the UK. London: Department of Energy and Climate Change; 2012. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65602/6927-energy-efficiency-strategy--the-energy-efficiency.pdf.

[44] DECC. Call for Evidence: Tackling NonFinancial Barriers to Gas CHP. London: Department of Energy and Climate Change; 2015. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/401962/Gas_CHP_Call_for_Evidence_-_Tackling_Non-Financial_Barriers_v6.pdf.

[45] DECC. Heat Networks Delivery Unit: Overview of grant funding and guidance available to local authorities developing heat networks. London: Department of Energy and Climate Change; 2014. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/270545/Decc-consultation-EED_heat_metering_and_billing_-_FINAL_100114.pdf.

[46] Ipsos MORI and EST. Research Report: Homeowners' Willingness To Take Up More Efficient Heating Systems. DECC; 2013. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/191541/More_efficient_heating_report_2204.pdf.

[47] DECC. Implementing the Energy Efficiency Directive as it applies to the metering and billing of heating and cooling. London: Department of Energy and Climate Change; 2014. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/270545/Decc-consultation-EED_heat_metering_and_billing_-_FINAL_100114.pdf.

[48] Directive 2004/8/EC. of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC. Brussels: Official Journal of the European Union; 2004. Available from: http://ec.europa.eu/energy/efficiency/cogeneration/cogeneration_en.htm.

[49] Directive 2006/32/EC. of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC (Text with EEA relevance). Brussels: Official Journal of the European Union; 2006. (L 114/64-85). Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0032&from=EN.

[50] Localism Act. Enacted 15 November 2011 Chapter 20.; 2011. Available from: http://www.legislation.gov.uk/ukpga/2011/20/pdfs/ukpga_20110020_en.pdf.

[51] Shipworth M, Firth SK, Gentry MI, Wright AJ, Shipworth DT, Lomas KJ. Central heating thermostat settings and timing: building demographics. Building Research & Information. 2010;38(1):50 – 69. Available from: http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=49154326&site=ehost-live.

[52] EEBPp. Good Practice Guide 302: Controls for domestic central heating and hot water guidance for specifiers and installers. In: Energy Efficiency Best Practice programme; 2001. Available from: http://www.draytoncontrols.co.uk/uploadedFiles/Drayton/Industry_Regulation/Good_Practise_Guide_302_ENG.pdf.

[53] Peffer T, Pritoni M, Meier A, Aragon C, Perry D. How people use thermostats in homes: A review. Building and Environment. 2011;46(12):2529 – 2541. Available from: http://www.sciencedirect.com/science/article/pii/S0360132311001739.

[54] Gill ZM, Tierney MJ, Pegg IM, Allan N. Low-energy dwellings: the contribution of behaviours to actual performance. Building Research & Information. 2010;38:491–

508. Available from: http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=53078751&site=ehost-live.

[55] DECC. Data tables: Green Deal, ECO and Insulation Levels, up to December 2013. London; 2014. Available from: https://www.gov.uk/government/statistics/green-deal-energy-company-obligation-eco-and-insulation-levels-in-great-britain-quarterly-report-to-december-2013.

[56] Yates T. Refurbishing Victorian housing - guidance and assessment method for sustainable refurbishment; 2006. Available from: http://www.brebookshop.com/details.jsp?id=286934.

[57] Wilson W. Housing Market Renewal Pathfinders; 2013. Available from: www.parliament.uk/briefing-papers/sn05953.pdf.

[58] Boardman B. Examining the carbon agenda via the 40% House scenario. Building Research & Information. 2007;35(4):363 – 378. Available from: http://www.tandfonline.com/doi/abs/10.1080/09613210701238276.

[59] DECC. Implementing the Energy Efficiency Directive as it applies to the metering and billing of heating and cooling. London: Department of Energy and Climate Change; 2014. (URN: 13D/314). Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/270545/Decc-consultation-EED_heat_metering_and_billing_-_FINAL_100114.pdf.

[60] Heat Network Metering and Billing Regulations. SI 2014/3120; 2014. Available from: http://www.legislation.gov.uk/uksi/2014/3120/pdfs/uksi_20143120_en.pdf.

[61] Poyry Energy Consulting. The potential and costs of distric heating networks: A report to the Department of Energy and Climate Change. Oxford: Department of Energy and Climate Change; 2009. Available from: http://webarchive.nationalarchives.gov.uk/20121205174605/http:

/decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/distributed%20energy%20heat/1467-potential-costs-district-heating-network.pdf.

[62] Routledge K, Williams J. District Heating - Heat Metering Cost Benefit Analysis. Building Research Establishment; 2012. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48389/5462-district-heating--heat-metering-cost-benefit-anal.pdf.

[63] BEAMA. Results of research carried out on the effectiveness of domestic heating controls by the University of Salford. London: BEAMA; 2013. Available from: http://www.beama.org.uk/download.cfm/docid/61F6E007-4278-4394-B3152ED04C12A0C8.

[64] Xu FL B, Di H. Dynamic simulation of space heating systems with radiators controlled by TRVs in buildings. Energy and Buildings. 2008;40(9):1755 – 1764.

[65] Munton T, Wright A, Mallaburn P, Boait P. How heating controls affect domestic energy demand: A Rapid Evidence Assessment. London: Department of Energy and Climate Change; 2014. (URN: 13D/337). Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/277552/FINALHow_heating_controls_affect_domestic_energy_demand_-_A_Rapid_Evidence_Assessment.pdf.

[66] SI 1995/418. Town and Country Planning (General Permitted Development) Order; 1995. Available from: http://www.legislation.gov.uk/uksi/1995/418/contents/made.

[67] Planning Act. Enacted: 26 November 2008, Chapter 29; 2008. Available from: http://www.legislation.gov.uk/ukpga/2008/29/contents.